Evapotranspiration

Consumptive Use Program Model

The California Department of Water Resources (DWR) and the University of California (UC) have developed a user-friendly Excel application program (CUP) to improve the dissemination of K_c and crop evapotranspiration (ET_c) information to California growers and water purveyors. CUP computes reference evapotranspiration (ET_o) from monthly means of solar radiation, maximum and minimum temperature, dew point temperature, and wind speed using the daily Penman-Monteith equation. The program uses a curve fitting technique to derive one year of daily weather and ET_o data from the monthly data. In addition, daily rainfall data are used to estimate bare soil evaporation as a function of mean of ET_o and wetting frequency in days. A bare soil K_c value is calculated to estimate the off-season evapotranspiration and as a baseline for in-season K_c calculations. CUP accounts for the influence of orchard cover crops on K_c values and it accounts for immaturity effects on K_c values for tree and vine crops. Further, the program computes and applies all ET_o and K_c values on a daily basis to determine crop water requirements by month, by season, by year.

Methodology

Reference Evapotranspiration (ET_o) Calculation

Reference evapotranspiration (ET_o) is estimated from daily weather data using a modified version of the Penman-Monteith equation [1]. The equation is:

$$ET_o = \frac{0.408\ \Delta\ (R_n\ -\ G)\ +\ \gamma\ \dfrac{900}{T\ +\ 273}\ u_2\ (e_s\ -\ e_a)}{\Delta\ +\ \gamma\ (1\ +\ 0.34\ u_2)} \qquad (1)$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve (kPa $^{\circ}$C^{-1}), R_n and G are the net radiation and soil heat flux density in MJ m^{-2}d^{-1}, γ is the psychrometric constant (kPa $^{\circ}$C^{-1}), T is the daily mean temperature ($^{\circ}$C), u_2 is the mean wind speed in m s^{-1}, e_s is the saturation vapor pressure (kPa) calculated from the mean air temperature ($^{\circ}$C) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature ($^{\circ}$C) for the day. The coefficient 0.408 converts the $R_n - G$ term from MJ m^{-2}d^{-1} to mm d^{-1} and the coefficient 900 combines together several constants and coverts units of the aerodynamic component to mm d^{-1}. The product 0.34 u_2, in the denominator, is an estimate of the ratio of the 0.12-m tall canopy surface resistance (r_c=70 s m^{-1}) to the aerodynamic resistance (r_a=205/u^2 s m^{-1}). It is assumed that the temperature, humidity and wind speed are measured between 1.5 m (5 ft) and 2.0 m (6.6 ft) above the grass-covered soil surface. If only temperature data are available, the Hargreaves-Samani equation is used. The equation may be written:

$$ET_o = 0.0023\ (T_c + 17.8)\ R_a\ (T_d)^{1/2} \qquad (2)$$

Where, T_c is the monthly mean temperature (degrees centigrade), R_a is the extraterrestrial solar radiation expressed in mm/month, and T_d is the difference between the mean minimum and mean maximum temperatures for the month ($^{\circ}$C).

If pan data are input into the program, then the program automatically converts monthly pan evaporation data to ET_o estimates using the latest methodology. The new method in the CUP estimates ET_o from *Epan* data using a fetch value (i.e., upwind distance of grass around the pan) without the need for wind speed and relative humidity data.

Validation and Comparison of CUP with Other Methods

Nine years of estimated daily ET_o data from CIMIS (California Irrigation Management Information System) at Davis, California were used to validate our model predictions of ET_o. Figure 1 compares daily mean ET_o estimates of CUP and CIMIS averaged over the period of the data set at Davis, California. The performance of the CUP was further evaluated at a humid location (Port Hueneme) and windy desert site (Bishop). As seen in Figures 1-3, a close agreement between CIMIS-based estimates of ET_o and those of the CUP model exists. Davis is in the Central Valley, which is characterized by clear, hot, dry days with strong, cooling southwest winds during afternoons in the summer. Port Hueneme is in Ventura County with coastal cool, humid weather patterns. Bishop is influenced by a windy desert environment on the eastern side of the Sierra Nevada range.

Figure 1
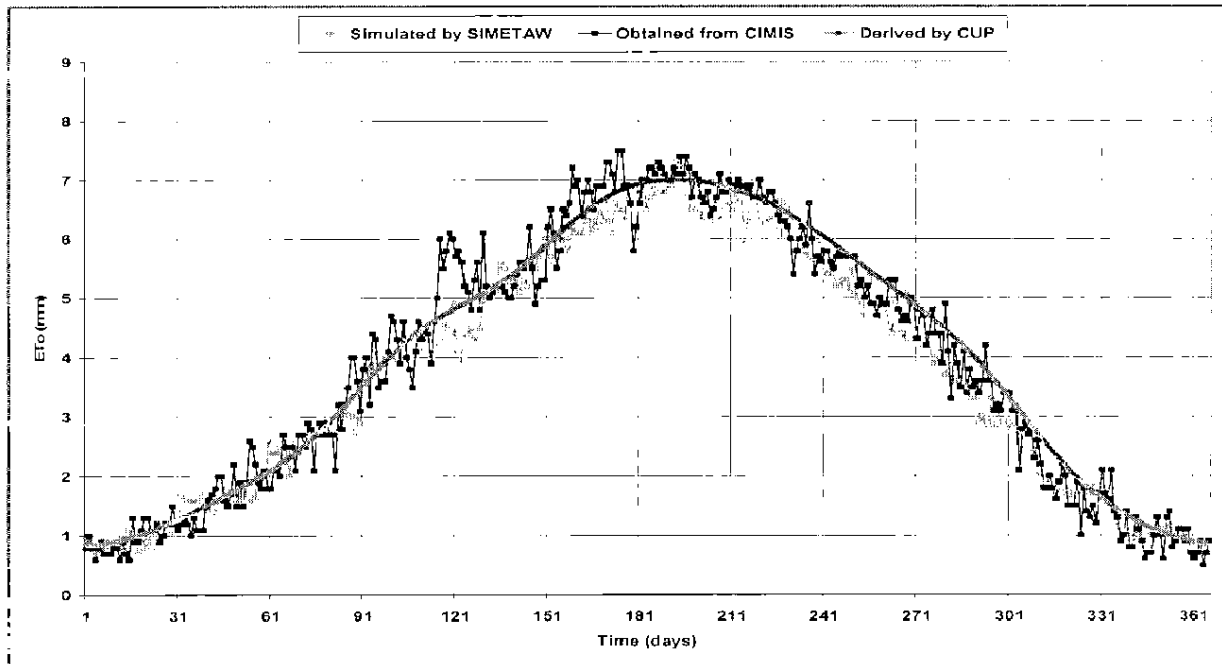**Comparison of daily *ET$_o$* estimates from CUP, SIMETAW, and CIMIS at Davis, California**

Figure 2
Comparison of daily *ET$_o$* estimates from CUP, SIMETAW
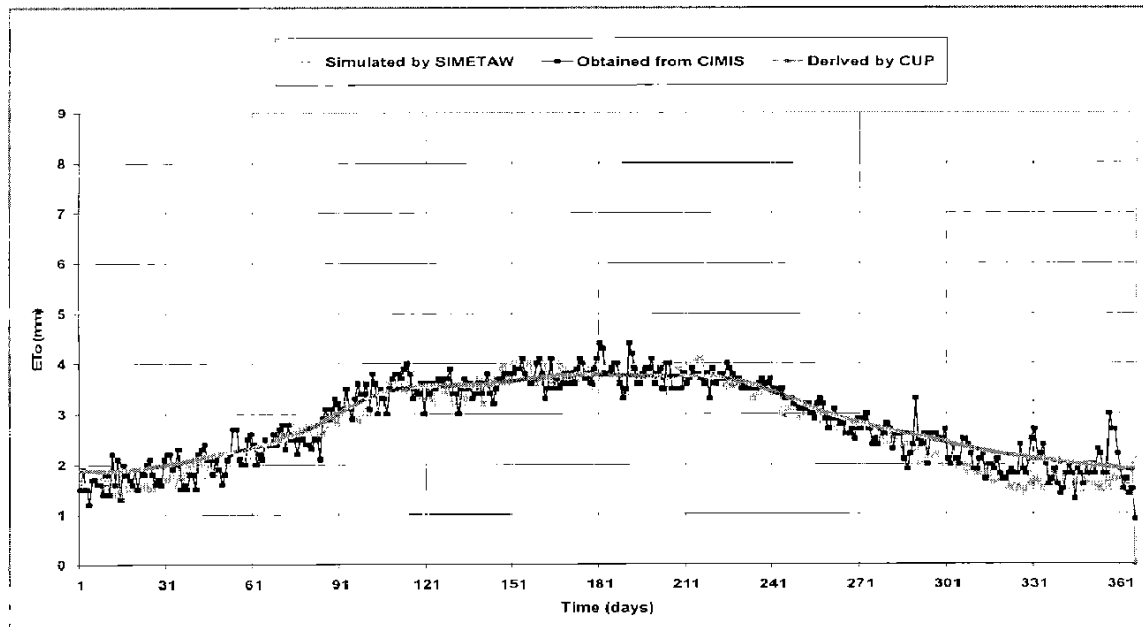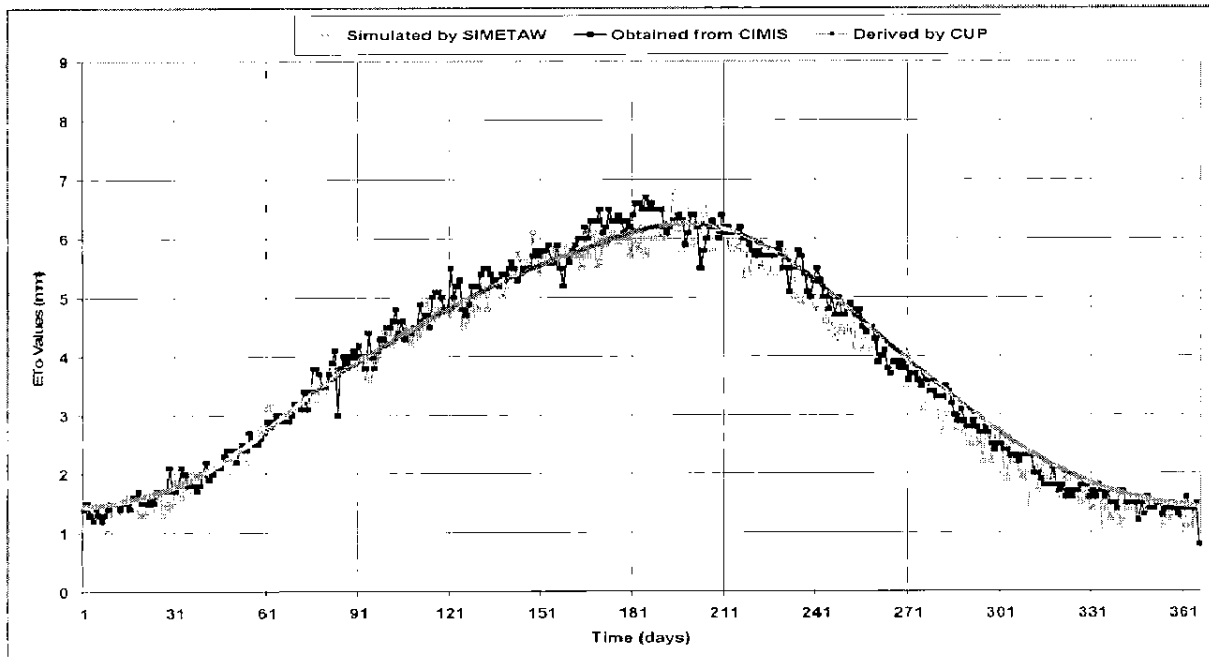**and CIMIS at Port Hueneme, California**

Figure 3
Comparison of daily *ET$_o$* estimates from CUP, SIMETAW, and CIMIS at Bishop, California

Daily Weather Output Accuracy

One of objectives of the CUP model is use a curve fitting technique to produce one year of daily weather data from 12 monthly mean values. Monthly mean values of measured weather data averaged over the period of the data set (1990 – 1998) from the California Irrigation Management Information System (CIMIS) in Davis were used in the model to derive one year of daily weather data. The weather data consist of R_s, T_{max}, T_{min}, wind speed, T_{dew}, and Rainfall. The weather data derived by CUP were compared with the measured and simulated data from CIMIS and SIMETAW, respectively. Results in Figures 4, 5, and 6 showed that R_s, T_{max}, and Rainfall values predicted from CUP were well correlated with those values obtained from CIMIS and SIMETAW. The performance of the CUP was further evaluated at a humid location and windy desert site. In all locations, CUP correlated very well with CIMIS and SIMETAW. Similar results were also observed for T_{min}, wind speed, and T_{dew} data in other locations.

Figure 4
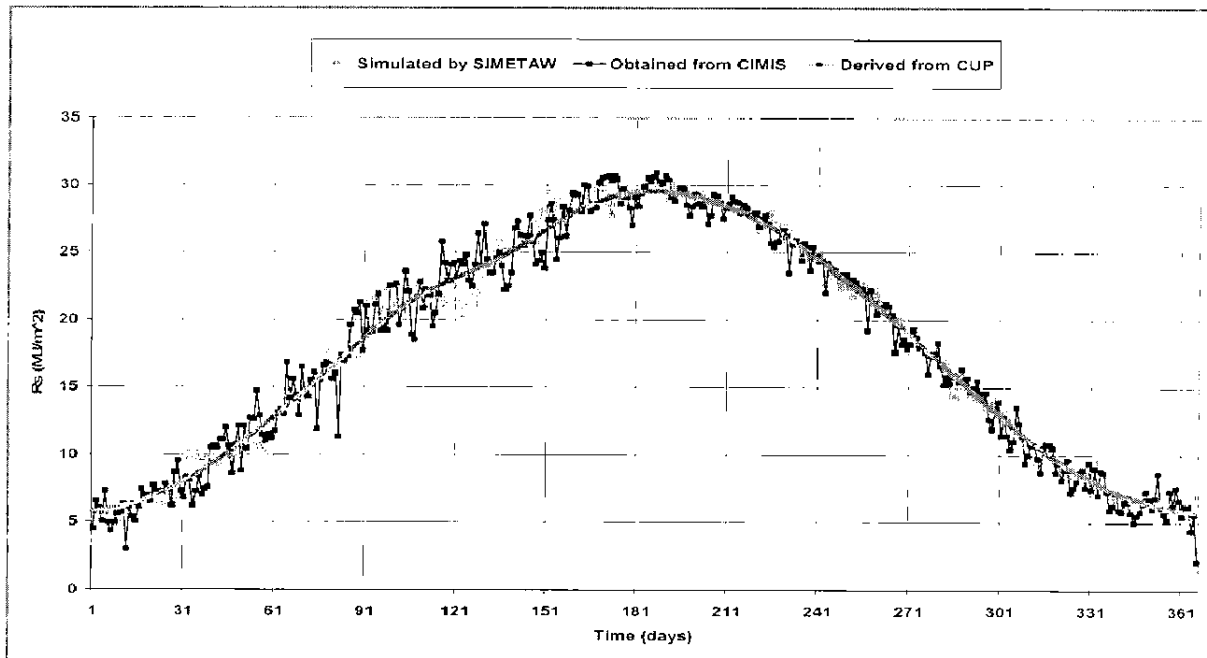**Comparison of measured and predicted daily solar radiation data at Davis, California**

Figure 5
Comparison of measured and predicted daily air maximum temperature data at Davis, California
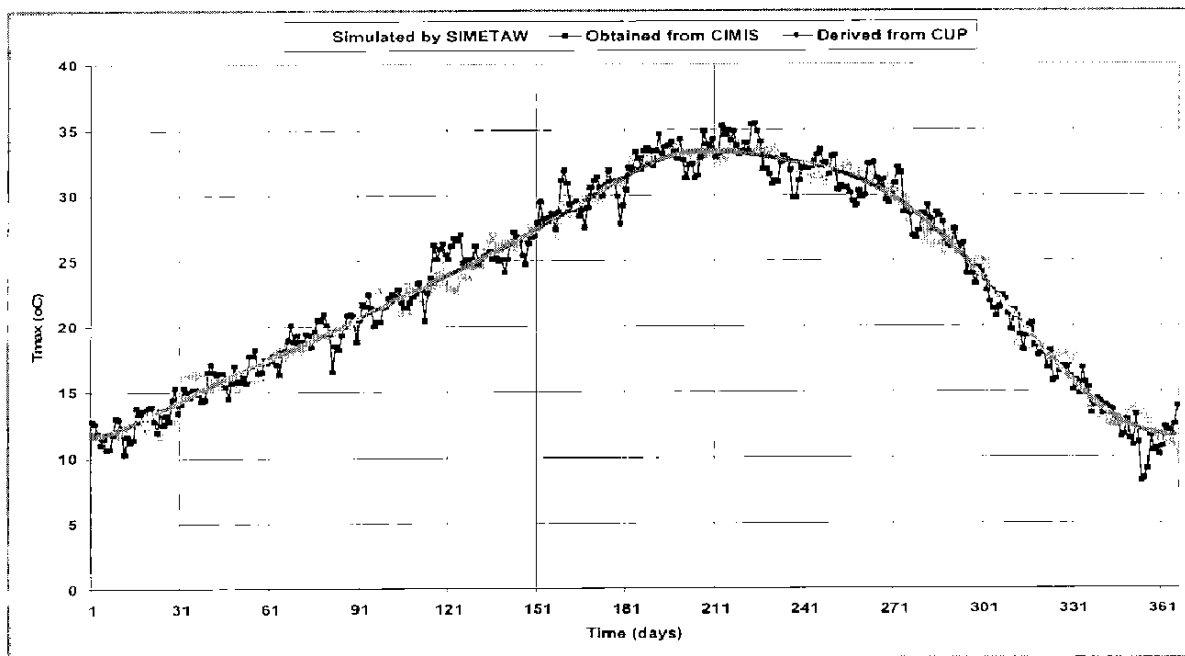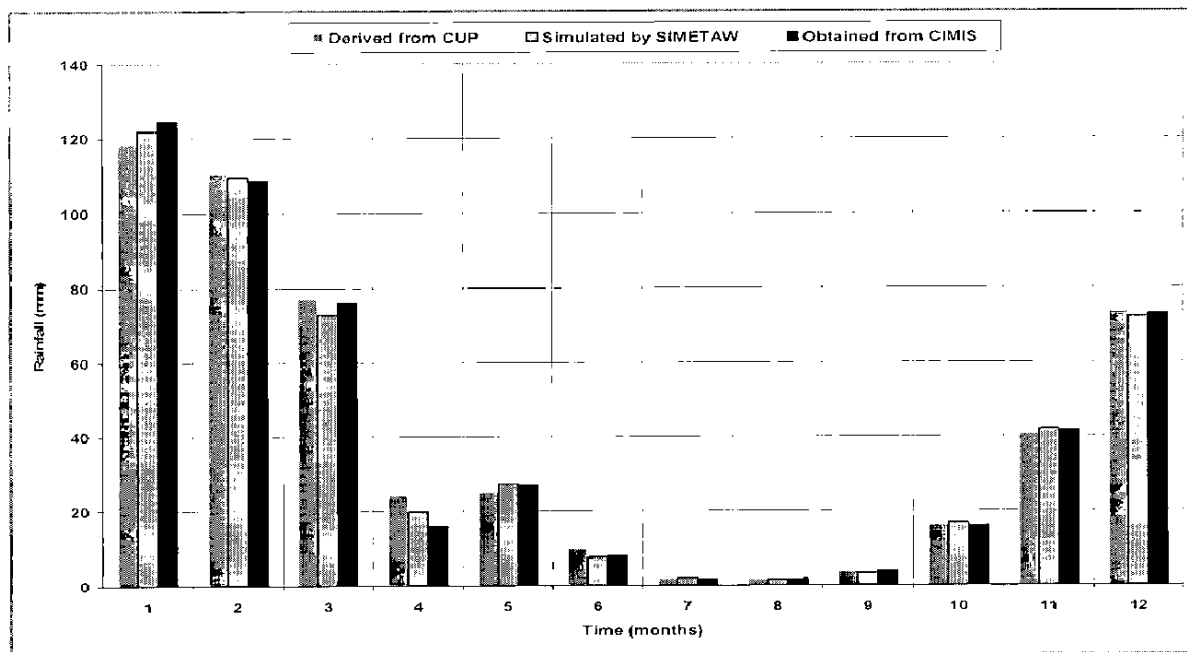
Figure 6
Comparison of monthly total rainfall values from three different methods at Davis, California

Worksheets

CUP has 19 Excel worksheets. The first eight worksheets are 'Disclaimer', 'HelpAbout', 'About Cup', 'HELP', 'ETo Zones Map', 'ETo Zones', 'Weather Input' and Input_Output'. 'HelpAbout' provides information about the program. 'About CUP' explains the program, 'HELP' explains the various components of the program and provides step-by-step instructions for inputting data into the program. 'ETo Zones' contains a map showing 18 zones of similar ET_o rates for California. The 'Weather Input' worksheet is used to input monthly mean weather or E_{pan} data to estimate ET_o (or monthly mean ET_o data directly) for estimating crop evapotranspiration (ET_c). If the solar radiation, temperature, humidity and wind speed data are input, then the Penman-Montieth equation is used to calculate ET_o. If only temperature data are input into the table, then the Hargreaves-Samani equation is used to calculate ET_o. If pan data are input, the program automatically estimates daily ET_o rates using a fetch value (i.e. upwind distance of grass around the pan). ET_o and crop data are entered into the 'Input_Output' worksheet, which then displays the summary of inputs and monthly and seasonal outputs. The 'Crop References' worksheet contains a list of crops, crop numbers, estimated growth date, and K_c information. 'Calculation' worksheet shows all of the growth date and K_c as well as the daily calculations of ET_o, K_c and ET_c for each of the growth periods. 'Weather Output' provides one year of daily solar radiation, maximum and minimum temperature, wind speed, dew point temperature, and rainfall data. CUP also outputs one year of daily calculated crop coefficients, ET_o, and ET_c data by crop in the 'Daily ETc-Output' worksheet. 'Monthly Output' provides monthly total values of ET_o, ET_c, and rainfall during the growing season and off-season.

The 'K_c Chart' worksheet shows a plot of the calculated seasonal crop coefficients with colored lines representing each growth period. 'ETo Chart' worksheet plots daily ET_o with different colored lines for each growth period. The 'ETo_ETc Chart' provides a bar graph of ET_o and ET_c totals by month during the growing season for the current crop information. There are also summary worksheets for K_c values, ET_o and ET_c. After data entry, the current crop information and calculated K_c data in the 'Input_Output' worksheet can be printed to one row in the 'Summary of Kc' worksheet. ET_o data are printed to 'Summary of ETo', and ET_c data are printed to 'Summary of ETc'.

Input-Output Worksheet

Crop information is entered into cells on the left-hand side of the 'Input_Output' worksheet. To use monthly mean weather, raw *ETo* and pan data, 88 is input into the California ET_o Zone number. Next a crop number is entered into the Crop Number cell. CUP provides a list of crops and crop numbers in the 'Crop References' worksheet. That worksheet also contains the percentage of the season to various growth dates (explained later), K_c values at critical growth points, and sample start and end dates for the season.

Note that the crop numbers have one digit to the left and two digits to the right of a decimal point. The single digit identifies the crop type, and the double digit identifies the crop. When a crop is selected, the growth, K_c and default start-end information is automatically used for the calculations. The start date corresponds to planting for field and row crops and to leaf-out date for tree and vine crops. Non-deciduous trees, turfgrass, and pasture crops start on January 1 and end on December 31. If different from the default values, the start and end dates can be changed in the 'Input_Output' worksheet.

The initial K_c value for most crops depends on wetting frequency from rainfall and/or irrigation. As the canopy shading increases, the contribution of soil evaporation to ET_c decreases while the contribution of transpiration increases. In the 'Input_Output' worksheet, the rainfall frequency during early growth is input to determine a K_c for near bare soil evaporation. Similarly, the irrigation frequency is entered and a K_c determined for near bare-soil evaporation during initial growth of field and row crops. CUP compares K_c values from the Crop References worksheet with those based on rainfall and irrigation frequency and selects the largest of the three for use in calculating ET_c. If no rainfall or irrigation frequency is entered, the K_c from the A-B column in the 'Crop References' worksheet is used as the initial growth K_c. The starting K_c for type-2 crops (for example, turfgrass and pasture) and for type-4 crops (for example, subtropical orchards) is not affected by the irrigation or rainfall frequency entries.

Cover crops affect ET_c rates, and CUP accounts for the contributions. The cover crop start and end dates are input into cells under the "Enter 1st Cover Crop (day/mon)." Because some crops have cover crops in spring and fall but not in the summer, a second set of cover crop dates can be input under "Enter 2nd Cover Crop (day/mon)". During a period with a cover crop, the value 0.35 is added to the "clean cultivated" K_c value. However, the K_c is not allowed to exceed 1.15 or to fall below 0.90.

The right-hand side of the 'Input_Output' worksheet shows the weighted mean K_c, ET_o, ET_c, and seasonal ET_c values by month for the selected crop and input information. The daily mean ET_o rates by month are also shown below the other data. Below that set of cells, there are "Copy/Paste" and "Delete" buttons. When the Copy/Paste button is pressed results of the calculations are sent to 'Summary ETo,' 'Summary Kc', and 'Summary ETc' worksheets. The Delete button clears all entries from the summary worksheets.

To retain all of the data entries, save the CUP file as an Excel workbook with a different name. To save only the summary sheets, with the summary sheet displayed, save as a tab or comma delimited file. After saving the desired output data, click the Delete button to erase data from the summary worksheets.
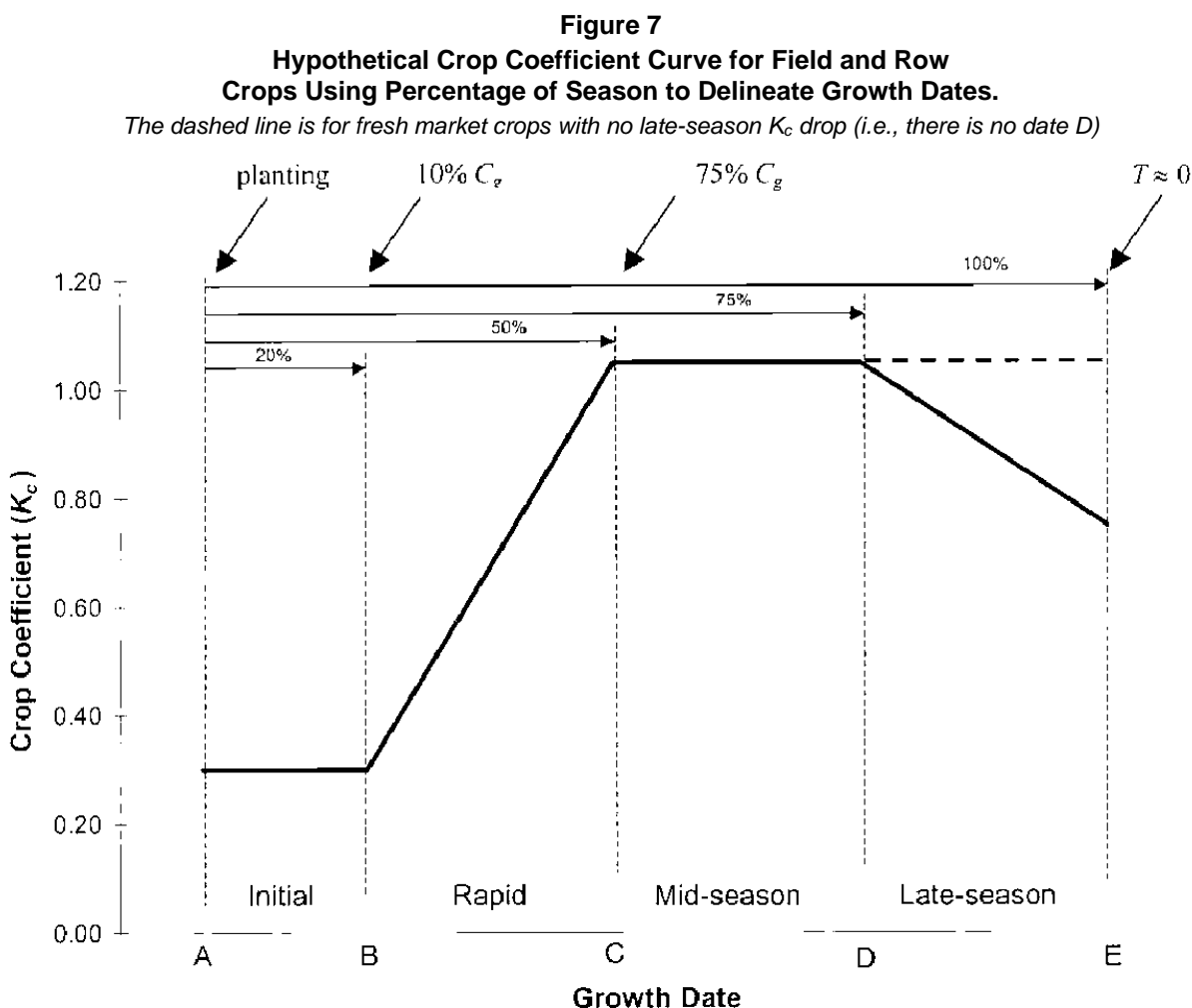
Calculation

The Calculation worksheet shows the selected and input data as well as critical dates for growth and cover crops and the daily calculations of ET_o, K_c and ET_c by the growth stages. The main factors affecting the difference between ET_c and ET_o are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age and (5) surface wetness. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. Therefore, for unstressed crops, solar radiation (or light) interception by the foliage and soil mainly affect the ET_c rate.

As field and row crops grow, the canopy cover, light interception, and the ratio of transpiration (T) to ET increases until most of the ET comes from T and evaporation (E) is a minor component. The K_c increases with canopy cover until reaching about 75 percent cover. For tree and vine crops the peak K_c is reached when the canopy has reached about 70 percent ground cover. The difference between the crop types is because the light interception is higher for the taller crops.

Field and Row Crop K_c Values

Field and row crop K_c values are calculated using a method similar to that described by Doorenbos and Pruitt [2]. A generalized curve is shown in Fig. 4. In their method, the season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods. K_c values are denoted K_cA, K_cB, K_cC, K_cD and K_cE at the ends of the A, B, C, D, and E growth dates, respectively. During initial growth, the K_c values are at a constant value, so $K_cA = K_cB$. During the rapid growth period, when the canopy increases from about 10 percent to 75 percent ground cover, the K_c value increases linearly from K_cB to K_cC. The K_c values are also at a constant value during midseason, so $K_cC = K_cD$. During late-season, the K_c values decrease linearly from K_cD to K_cE at the end of the season.

Figure 7
Hypothetical Crop Coefficient Curve for Field and Row
Crops Using Percentage of Season to Delineate Growth Dates.
The dashed line is for fresh market crops with no late-season Kc drop (i.e., there is no date D)

Doorenbos and Pruitt [2] provide estimated number of days for each of the four growth periods to help identify the end dates of growth periods. However, because there are climate and varietal differences and because it is difficult for growers to know when the inflection points occur, irrigators often find this confusing. To simplify this problem, percentages of the season from planting to each inflection point rather than days in growth periods are used (Fig. 4). Irrigation planners need only enter the planting and end dates and the intermediate dates are determined from the percentages, which are easily stored in a computer program.

During initial growth of field and row crops, the default K_c value (K_c1) is used for K_cA and K_cB unless it is overridden by entering a K_c based on rainfall or irrigation frequency. If a soil wetting based K_c1 is desired, the irrigation or rainfall frequency is entered in the 'Input_Output' worksheet.

The values for $K_cC = K_cD$ depend on the difference in (1) light interception, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop. Some field crops are harvested before senescence, and there is no late season drop in K_c (for example, silage corn and fresh market tomatoes). Relatively constant annual Kc values are possible for some crops (for example, turfgrass and pasture) with little loss in accuracy.

Deciduous Tree and Vine Crop K_c Values

Deciduous tree and vine crops, without a cover crop, have K_c curves that are similar to field and row crops but without the initial growth period (Fig. 5). Default K_cB, $K_cC = K_cD = K_c2$ and $K_cE = K_c3$ values are given in the Crop References worksheet of the CUP. The season begins with rapid growth at leaf out when the K_c increases from K_cB to K_cC. The midseason period begins at approximately 70 percent ground cover. Then, unless the crop is immature, the K_c is fixed between dates C and D, which corresponds to the onset of senescence. For immature crops, the canopy cover may be less than 70 percent during the midseason period. If so, the K_c will increase from K_cC up to the K_cD as the canopy cover increases, so the CUP program accounts for K_c changes of immature tree and vine crops. During late season, the K_c decreases from K_cD to K_cE, which occurs when the transpiration is near zero.

Figure 8:
Hypothetical Crop Coefficient Curve for Deciduous Tree and
Vine Crops Using Percentage of the Season to Delineate Growth Dates
There is no initial growth period, so the season starts at leaf out on date B
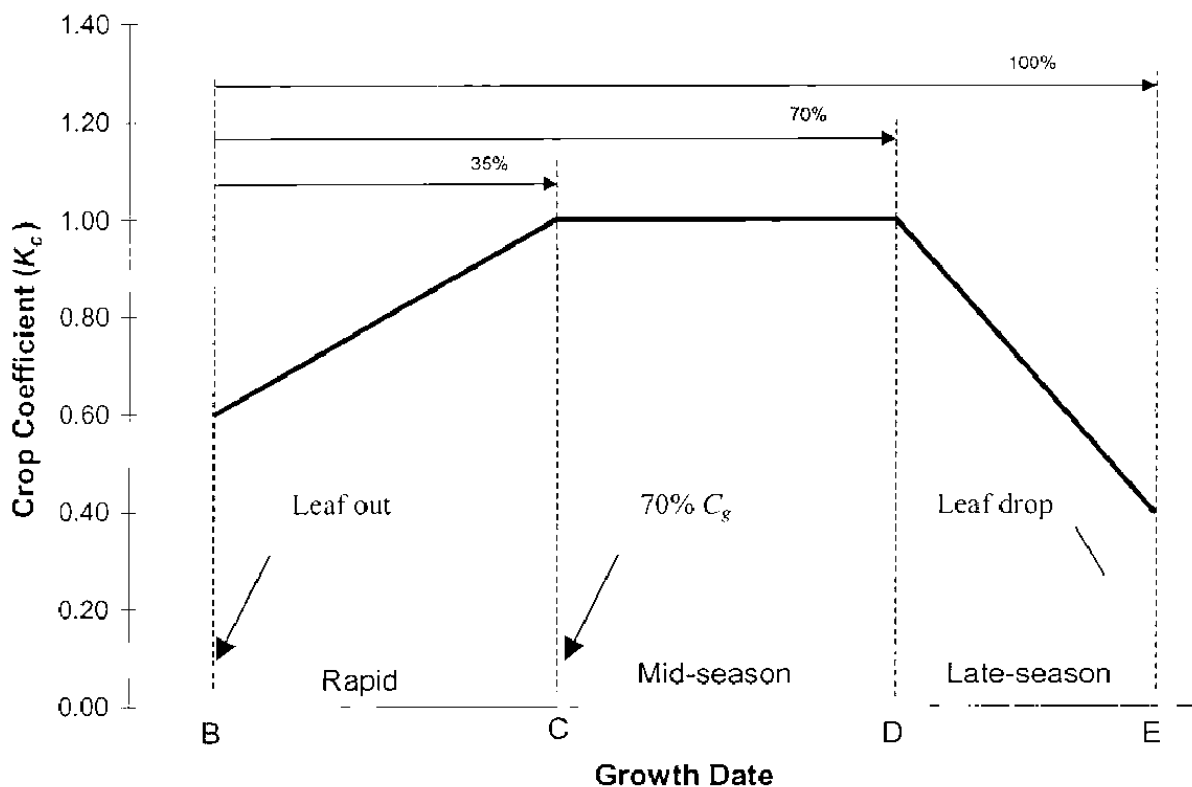
Correcting K_cB for Soil Evaporation

Initially, the K_c value for deciduous trees and vines (K_cB) is selected from a table of default values. However, the *ET* is mainly soil evaporation at leaf out, so CUP contains the methodology to determine a corrected K_cB, based on the bare soil evaporation.

Correcting for Cover Crops

With a cover crop, the K_c values for deciduous trees and vines are higher. When a cover crop is present, 0.35 is added to the clean-cultivated K_c. However, the K_c is not allowed to exceed 1.15 or to fall below 0.90. CUP allows the beginning and end dates to be entered for two periods when a cover crop is present in an orchard or vineyard.

Immature Trees and Vines

Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature K_c values (K_{cm}) as a function of percentage ground cover (C_g).

(3)

$$\text{If } \sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_{cm}\sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)}$$

Subtropical Orchards

For mature subtropical orchards (for example, citrus), using a fixed K_c during the season provides acceptable ET_c estimates. However, if higher, the bare soil K_c is used for the orchard K_c. For an immature orchard, the mature K_c values (K_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

(4)

$$\text{If } \sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_{cm}\sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)}$$

Field Crops and Landscape Covers with Fixed K_c Values

Some field crops and landscape plants (type-2 crops) have fixed K_c values all year. However, if the significant rainfall frequency is sufficient to have a higher Kc for bare soil than for the selected crop, then the higher bare soil K_c should be used. CUP permits entry of monthly mean rainfall frequency data. If entered, daily Kc values for bare soil evaporation are computed for the entire year. The higher of the fixed crop K_c or the bare soil K_c is used to estimate ET_c for the crop. If no rainfall frequency data are entered, then the fixed crop K_c is used.

Estimating Bare Soil K_c Values

A soil evaporation K_c value, based on ET_o and rainfall frequency is needed as a minimum (base line) for estimating ET_c. It is also useful to determine the K_c value during initial growth of field and row crops ($K_c1 = K_cA = K_cB$), based on irrigation frequency, and the starting K_c for deciduous tree and vine crops ($K_c1 = K_cB$). The K_c values used to estimate bare soil evaporation are based on a two-stage soil evaporation method reported by Stroosnjider [4] and refined by Snyder et al. [3]. The method provides a

K_c values as a function of ETo rate and wetting frequency that are similar to those published in Doorenbos and Pruitt [2].

If the mean monthly weather and ET_o data are input into the Weather Input worksheet, including the number of significant rainy days per month, CUP calculates a baseline soil evaporation curve. Daily precipitation is considered significant when Ps > 2×ET_o. Whenever, the K_c for bare soil evaporation is bigger than the K_c based on table or calculated K_c values, the higher K_c value is used.

Extra Features of CUP

CUP application program was written using MS Excel software as a tool to help water agencies, engineers, consultants, educators, and growers obtain accurate estimates of crop water requirement information from monthly mean data. The program takes input weather data and estimates historical means of reference evapotranspiration (ET_o) using the Penman-Montieth equation, If only temperature data are available, the Hargreaves-Samani equation is used. CUP also converts monthly pan evaporation data to ET_o estimates using the latest methodology. In addition, the CUP estimates the annual trend in daily ET_o and weather data. In the past, only monthly, bi-weekly or weekly data were available in the literature and using daily data from CUP improves the ET_c estimation. Alternatively, CUP can select monthly ET_o values from the California ET_o map and it can estimate ET_o from class 'A' pan evaporation using the latest conversion methods. The program helps users to determine improved crop coefficient (K_c) values for estimating crop evapotranspiration (ET_c). Rather than using only linear estimates of the K_c values for various growth stages the CUP accounts for differences in soil evaporation to refine the early season K_c values. The CUP can be used as a tool for teaching and conducting research. In addition, the application outputs a wide range of tables and charts that are useful for irrigation planning. CUP's input and output data are in both English and metric units.

More information on CUP is available at DWR's Web site:
www.waterplan.water.ca.gov/landwateruse/wateruse/Ag/wuagricultural.htm

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Evapotranspiration and Relative Contribution by the Soil and the Plant

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Introduction

A field receives water as rain or irrigation. Some of this water may be lost in liquid form as runoff. Some, after infiltrating the soil, may continue to move deeper as liquid beyond the root zone and into the ground water. Usually, the major loss of water is as vapor, by evaporating from the soil or being transpired by the plants growing on the soil. The liquid loss can be recovered either as ground water or stream flow by users downstream. The water lost as vapor is dissipated in the atmosphere, a huge sink, and cannot be recovered except as precipitation. For all intents and purposes, evapotranspiration from a field, consisting of both water transpired by plants and evaporated from the soil, represents an irreversible loss from that geographical location, and is referred to as consumptive water use.

Evapotranspiration or consumptive water use is usually beneficial, in that plants are grown and produced in exchange for the water used. Plants grow and acquire their biomass (dry weight) by assimilating carbon dioxide from the air via photosynthesis. To acquire carbon dioxide from the air, plants open their stomata, the microscopic control valves on the leaf surface, to let carbon dioxide diffuse into the leaves for photosynthesis. At the same time, water vapor escapes inevitably via the same open valves into the atmosphere. Hence, carbon dioxide assimilation and transpiration (T) are closely associated, and high production is usually linked to high crop water use, as long as that use is the result of transpiration (Tanner and Sinclair, 1983; Hsiao, 1993).

The consumptive use of water through soil evaporation (E), however, is not in exchange for carbon dioxide assimilation. Therefore it is usually considered to be non-beneficial use. This point of view is perhaps slightly too simplistic, and will be discussed in a later section. In any event, in managing the limited water resource of the state of California, it is important to know more accurately how much water crop fields evapotranspire, and how much of the evapotranspiration is due to soil E. It is also important to devise and develop means to minimize the E part of ET. This chapter presents pertinent information bearing on these points and is made up of two parts. The first part discusses ET in terms of the basic principles and important factors determining ET and the quantitative relationships. That is followed by a brief description of the methods used to separate out soil E from plant T, and a review of the literature quantifying the extent of soil E relative to ET. The second part reports on the results of experiments conducted to obtain additional information on the factors affecting ET and the proportion of E in ET, the extent ET is suppressed while water is applied by sprinklers, and the extent that crop T is likely to be increased by minimizing soil E.

Conceptual Background and Analysis of the Literature

Energy Supply for Evapotranspiration and Interactions Between E and T

For water to be evapotranspired, it must be converted from liquid form to vapor form. Water has an unusually high latent heat of vaporization—it takes approximately 2.45 kJ (580 calories) of energy to evaporate one gram of water. For a crop field, virtually all of this energy comes from the aerial

environment. By far the most important source of energy for ET is solar radiation absorbed by the field. This is known as net radiation transfer and consists of the incoming radiation minus the outgoing radiation. A minor source is the direct heating of the crop and soil by air going over the field, which occurs only when the air is warmer than the crop and the soil. This energy supply is termed sensible heat transfer. For many situations, the absorbed radiation is so dominating that daily or weekly ET from a fully wet field can be estimated from the net radiation over the field for the same period. The energy supplied by net radiation is divided by the latent heat of vaporization to obtain the amount of water evapotranspired. Such estimates often fall within 5 or 10 percent of the true ET. Deviation is caused by the warming or cooling of the field by the overhead air mass. ET (when converted to energy units) would be greater than net radiation if the air has a net warming effect on the field, and would be less if the air is mostly cooler than the field and has a net cooling effect.

If the rate of energy supplied as net radiation is suddenly reduced for an evapotranspiring field by a passing cloud blocking the sun, ET would continue for a very short moment (seconds to minutes) at nearly the same rate, but with part of the energy supplied by the sun for evaporation now coming from the heat stored in the crop and soil. The loss of the stored heat to the evaporation process reduces the temperature of the crop and the soil. The cooler temperature then leads to a lower water vapor concentration in the crop and at the soil surface, which in turn slows down ET quickly after the cloud blocks the sun. If the energy supply is suddenly increased as the cloud moves away and the sun reappears, or by a warm wind, ET would remain momentarily at near the original rate, until the extra energy heats up the crop and soil. The higher temperature then raises the water vapor concentration in the leaves and at the soil surface, leading to an increase in ET.

Water vapor concentration in leaves and at the soil surface change with temperature because saturation water vapor concentration is strongly dependent on temperature, rising as temperature of the water increases (Clausius0-Clapeyron equation). The air space network inside leaves is essentially saturated with water vapor. For any given soil water status (soil moisture tension), the air layer a few molecules thick adjacent to the soil is also nearly saturated with water vapor. Hence, changes in temperature of the leaves and the soil are associated with changes in water vapor concentration at the water losing surface.

Under favorable conditions with ample water supply when leaves are photosynthesizing at a high rate, stomata of most crop species are essentially fully open. In that case the foliage canopy acts essentially as a fully wet surface, transpiring at a rate similar to evaporation from a free body of water at the same temperature, covering the same land area as the canopy, and under the same aerial environment. This rate may be loosely referred to as the potential rate of transpiration, evaporation, or evapotranspiration. When plants are deficient in water or nutrients, and when temperature is too cold, stomata are less open and photosynthesis rate lower, the canopy would act as a surface that is less than fully wet, and transpiration would be below the potential rate. For the soil, evaporation is at the potential rate when the surface is fully wet and vapor concentration essentially the same as that of a body of water at the same temperature. When the soil surface begins to dry out and surface vapor concentration falls significantly below that of free water at the same temperature, soil E would fall below the potential rate.

Crop fields may be considered to be composed of three types of surfaces-canopy surface, exposed soil surface, and shaded and sheltered soil surface. Shaded soil surface receives very little radiation and is at a temperature considerably lower than that of exposed soil. This, coupled with the fact that it is generally subjected to less wind and under air of higher humidity because of transpiration of the canopy overhead,

limit its evaporation to a very low level. Consequently, one may assume that ET from a crop field is largely due to T from the canopy and E from the exposed soil surface. For situations of fully wet exposed soil surface and canopy with fully open stomata, the field acts as a fully wet surface as a whole, and evapotranspires at essentially the potential rate or slightly higher. For situations of partial canopy coverage of the soil combined with dry or not fully wet exposed soil, the field would evapotranspire at a rate lower than the potential and acts effectively as a surface that has dried to some degree.

Reference ET and Crop Coefficient

When the surface is fully wet, ET is at the potential rate determined by atmospheric conditions. The important weather variables are radiation, temperature, water vapor concentration (humidity) in the air, and wind velocity. An integrated measure of the capability of the atmosphere to supply the energy for ET and carry away the water vapor is reference evapotranspiration (ET_o). ET_o is defined as "the rate of ET from an extended surface of a short green crop (usually a grass kept short by frequent mowing), completely shading the ground and not short of water or nutrients"**.** For practical purposes, ET_o is either the same or very similar to potential ET and may assumed to be the same. Instead of being measured on grasses, ET_o is now commonly calculated from weather data using certain formula, or derived from pan evaporation data. Sufficient research has been done previously to verify that the calculated results are in close agreement with the results measured on grass as a reference crop (Doorenbos and Pruitt, 1975). For different locations in California, the Department of Water Resources collects the weather data from a network of weather stations and makes the ET_o data available for downloading from its web site. Although defined with grass as a reference crop, ET_o takes into account the effects of weather and is indicative of the evaporative demand of the atmosphere. The influence exerted by the crop and the soil on ET, however, is not included in ET_o. Crop and soil exert their control on ET mostly by altering the wetness of their surfaces. To a minor degree the roughness of the field, mostly determined by geometry of the vegetation, also exerts an effect. A rougher surface causes air moving over it to be more turbulent, enhancing the rate of ET slightly. In the common practical method of estimating ET, the impact of the crop and the soil is accounted for by a coefficient known as crop coefficient (K_c). K_c is defined as the ratio of crop ET to ET_o, such that:

$$ET = K_c \, ET_o$$

Thus, K_c is essentially an integrated measure of the "effective wetness" and roughness of the surface of the field, while ET_o is an integrated measure of the evaporative demand of the atmosphere. Another way to consider K_c is to think of it as ET of the crop normalized for the evaporative demand of the atmosphere. The simple equation holds for different time intervals chosen, ranging from hourly ET to weekly and monthly means.

Seasonal Pattern of ET of Annual Crops

The life cycle of annual crops may be divided into three phases, each characterized by its own ET rate and somewhat different response to environmental or management factors. During the first phase, the foliage canopy, very sparse at the beginning, grows with time until it fully or nearly fully covers the soil. The second phase, usually lasting for several weeks or more, consists of the time period when the canopy is full and green with no obvious yellowing. This is the period when the crop produces dry matter at the highest rate due to high rates of photosynthesis per unit of land area. The third phase starts as the crop begins to mature and the older leaves senesce and turn yellow first, followed by younger and younger leaves, until the crop is fully mature or harvested.

An example of the pattern of ET of an annual crop over the first two phases plus the beginning of the third phase is given in Figure 1. ET_o calculated from weather data is depicted by the dashed line. Effects of day-to-day variations in weather on ET are discernible as indicated by the variations in ET_o. More importantly, features attributable to the development of crop canopy cover and changes soil surface wetness stand out in Figure 1. For the first half of the graph, there is a gradual rise in base-line ET that can be visualized if one draws an imaginary smooth curve connecting the lowest ET rates for the first half of the graph. Added to this base line are several skewed ET peaks occurring after each irrigation. The peaks (referred to simply as irrigation spikes) are due to evaporation from the exposed soil surface after it is wetted by the irrigation water. As the soil surface begins to dry one or two days after an irrigation, soil E declines with time. The basal ET is due mostly to transpiration from the crop, plus some residual evaporation from the exposed soil at its driest point. In the first two or three weeks after planting, the plants have only very few leaves and the canopy covers only an insignificant portion of the ground. Therefore soil E accounts for virtually all of the ET. As the canopy of the crop develops, more and more of the ground is covered by the canopy, which continues to transpire regardless of the wetness of the soil surface, as long as the crop is obtaining sufficient water from the deeper part of the soil to keep its stomata open. Hence, base line ET rises with time in Figure 1, until the canopy covers the ground nearly fully.

With full ground cover, the canopy intercepts nearly all the radiation energy and accounts for most of the ET and soil E is not of much significance. ET is then insensitive to the wetting of the soil surface under the canopy, and hence is not affected perceptively by irrigation. In Fig. 1, the soil was mostly covered by the crop canopy about 55 days after planting. There were therefore no marked irrigation spikes in ET after that time, in spite of the irrigations. Near the end of the time interval shown in Fig. 1, older leaves of the canopy begin to turn yellow. This senescence apparently accounted for the decline in ET relative to ET_o at that time. The dip in ET on days 54, 66, 74, and 75 after planting were the result of cloudy and cool weather as indicated by the low values of ET_o on those days.
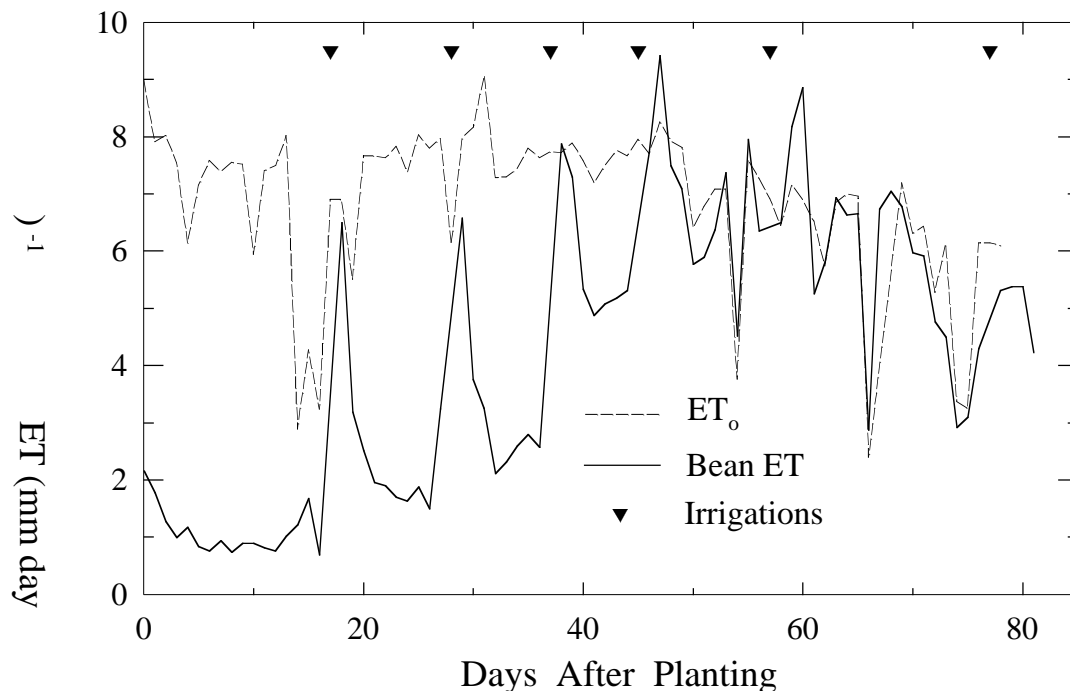
Figure 1. Daily evapotranspiration from a bean (*Phaseolus vulgaris*) crop planted at a density of 19 plants m^{-2} in rows 76 cm apart and measured on a 6.1 M diameter lysimeter. Also given is reference evapotranspiration (ET$_o$) provided by the nearby CIMIS weather station, at Davis, California. Summer, 1982. Inverted triangles indicate the days of sprinkler irrigation. Reproduced from Hsiao (1990).

In terms of K$_c$, it is easily deduced from Fig. 1 that early in the season, K$_c$ is close to 1.0 only right after each irrigation because ET is close to ET$_o$ only then. Right after an irrigation the exposed soil surface is wet, and the canopy as usual, acts as a wet surface. Afterwards K$_c$ falls rapidly below 1.0 as ET falls rapidly below ET$_o$ because the effective wetness of the overall surface is decreasing due to drying of the exposed soil surface. After the canopy covers the ground nearly completely from day 55 onward, the value of K$_c$ is close to 1.0 as ET tracks ET$_o$ closely. The surface of the field stays fully wet during that time because the crop, fully covering the soil, is well supplied with water and its stomata are fully open. Near the end of the period depicted in Fig. 1, K$_c$ falls below 1.0 as ET falls below ET$_o$ due to the beginning of senescence of the canopy.

The impact of leaf senescence on canopy ET and K$_c$ is more clearly seen in another study on maize (Steduto and Hsiao, 1998). ET was measured on a dry treatment growing only on water stored in the soil and on a wet treatment (control) that was irrigated regularly. As shown in Fig. 2, due to water deficit the dry treatment senesced earlier; its green leaf area started to declined around 95 DAP, with the LAI falling from a value of 6 to about 1.5 over a period of 20 days. The LAI of the control also fell at about the same rate, but started considerably later, at around 110 DAP. Consequently, K$_c$ declined considerably earlier for the dry treatment than the wet treatment. There is some indication that a part of the difference in K$_c$ is the result of reduced stomatal opening in the dry treatment, but most of the effect is due to leaf senescence induced by water deficit (Steduto and Hsiao, 1998).
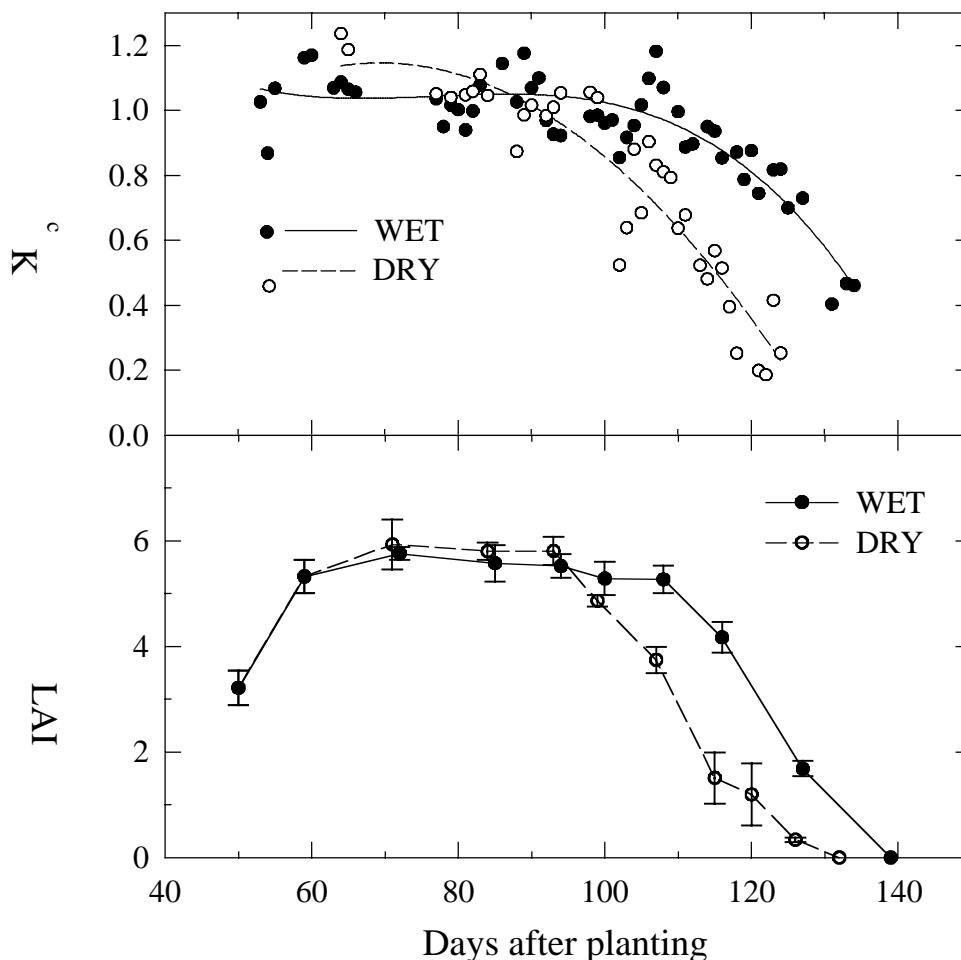
Figure 2. Daily crop coefficient (Kc) calculated as ET/ETo from sunrise to sunset and LAI (green leaves only) of corn grown on water stored in the soil (DRY) or with frequent irrigation (WET). ET was measured by the Bowen ratio/energy balance technique. Modified from Steduto and Hsiao (1998).

In contrast to the relatively smooth curves of K_c vs. time one finds in most irrigation books (often in tabulated form), the value of K_c deduced from Fig. 1 varies sharply from day to day for the first half of the figure. To a lesser extent that is also the case for the data in Fig. 2. That is because curves of K_c in books are usually smoothed out to represent the mean value over a long period. It is clear that during the first phase of the life cycle of a crop, K_c would vary with the number of irrigation spikes and area under the spikes and under the base-line ET. These in turn, will depend on the frequency of wetting of exposed soil surface and on the degree of canopy cover. Thus, K_c would be dependent on rainfall events and on the schedule of irrigation, as well as on the starting canopy cover and the rate of canopy development. Starting canopy cover in turn is partly dependent on density of the planting. Since all these items vary from location to location depending on conditions, K_c for the first phase would vary also. Thus, values of K_c for the first phase taken from the literature can only serve as a very rough approximation, and should be adjusted according to location conditions and practices. Similarly, because the starting time and rate of canopy senescence are usually affected by crop nutritional status, water deficit and temperature regimes, K_c for the third phase also can only be taken as approximation and should be adjusted for the time of onset and rate of senescence.

The preceding discussion also makes clear that not only the total ET, but the proportion of soil E making up ET depends too on the frequency of wetting of soil surface and the degree of canopy cover, and hence, should vary with local conditions and practices. At the same time, the discussion points to some possible options to reduce the E portion of ET, a topic to be taken up later. First, it is necessary to know how much of ET is due to soil E and under what conditions.

Measuring or Estimating E and T Separately

A fair number of papers have been published reporting separate estimates of soil E and plant T. Before considering these data and judging their reliability, it is necessary to consider the difficulties involved in making these estimate and review the methods used.

It may appear to be simple to separate out the rate of plant transpiration (T) from soil evaporation (E). In fact it is difficult to do. One important reason is that the plants and the soil share the same energy source and the same or closely overlapping aerial environment; therefore T and E interact. For example, in the case of a partial canopy cover with a substantial portion of the soil surface exposed and wet, soil E would cool the surface soil and the adjacent air, and humidify the adjacent air. Hence, the plants would be cooler and transpiring in a more humid environment, and T would be less compared with the situation when the soil surface is dry. If exposed soil between plants is covered to eliminate E, plant T would increase to some extent because the energy that would have gone to support soil E is now partly available to enhance plant T.

Another cause of the difficulties encountered in separating out T from E is the fact that the water evaporated from the soil or transpired from the plants comes ultimately from the same reservoir in the soil, and the rate of water depletion from this reservoir determines how wet or dry the soil surface would be and its rate of E. If one isolates a portion of the soil in a container to measure E from that portion, there would be no root removal of water from that portion, nor drainage or capillary rise of water from the soil layer below. This will lead in time to a soil surface different in wetness and vapor concentration than that of the non-isolated soil.

Since soil E and T interact, either of them can be measured simply by eliminating the other. Measuring the rate of water loss after removing the plants would overestimate E, and measuring after sealing the soil surface to eliminate soil E would overestimate T. In both cases the measured rates would be higher than the rate taking place with the original spatial pattern of plants on the soil, because eliminating one liquid-to-vapor conversion process would make the air drier and more energy available for the other process. It is necessary to measure one in the presence of the other to obtain realistic values. There are only a few ways to do this directly, and more ways to do it indirectly.

For fields with crops growing soil E is normally measured with microlysimeters, made by filling small (e.g., 1-liter) containers with the soil and burying the containers between crop rows. The weight loss of the microlysimeters over time on an area basis provides a measure of soil E for the field. For the measurement to be reliable, the following conditions must hold: (a) The position of the microlysimeters relative to the plants must be representative of the field. This is normally achieved by placing several lysimeters at equal distance between two plant rows, and replicating the lysimeter arrays at several locations. (b) The surface of the soil in the microlysimeter must be similar to that outside in smoothness and consolidation. This can be achieved by fitting an virtually intact core of soil in the lysimeter, or by

packing disturbed soil inside the lysimeter and letting the soil consolidate over one or more wetting/drying cycles. (c) The soil surface within the lysimeter must be nearly identical in water status as that of the soil adjacent to the lysimeters. This is difficult to achieve if the lysimeter, once installed, is used over a long period, because the soil inside is hydraulically isolated from that outside and roots are not inside the lysimeter to remove the soil water as it occurs outside. This problem can be overcome by installing sets of lysimeters frequently and measuring the weight loss of each set only over a short interval of a day or two. Alternatively, a large number of lysimeters may be installed, watered in a way to obtain a narrow range of surface wetness similar to that of the soil outside, and then measuring the weight loss only of those with wetness of the soil surface matching that outside. Wetness of the surface can be matched by measuring surface temperature with an infrared thermometer and choosing only lysimeters with surface temperature nearly identical to that of the soil outside under similar canopy shading. Unfortunately, to our knowledge this promising method, although alluded to in a publication (Walker, 1984), has rarely been applied to making measurement of soil E. Another way to ensure the match is to measure vapor pressure of the soil surface inside the lysimeters with the instrument of Seymour and Hsiao (1984).

Soil E has also been estimated from measured changes in water content of shallow layers of surface soil over time. This procedure is fraught with problems because water content may be changed by root water removal and vertical water movement within the soil, in addition to surface evaporation. Ritchie and Burnett (1971) ameliorated a part of this problem by relating lysimeter measured bare soil E rate to surface (3 cm layer) soil water content and using the relationship to deduce soil E from measured surface soil water content. This does not, however, take care of the root water removal problem. Another way to estimate soil E is to apply the Bowen ratio/energy balance (BREB) approach to measure the upward latent heat flux in the air very close to the surface of the soil between widely spaced crop rows (Ashktorab et al., 1994). Though novel, the estimates are likely confounded since gradients of temperature and humidity in the horizontal direction are probably marked and the normal fetch requirement for using the BREB technique is not met.

As for transpiration, T of single plants is now estimated by measuring the rate of upward flow of water in the plant stem. The assumption is that this rate is equal to the rate of T, a good assumption when measuring over a 24-hour period. When the measurement covers shorter periods (e.g., hourly), the results can be quite inaccurate because there is usually a substantial lag in the upward water flow behind transpiration in the morning, and in the transpiration behind the upward flow in the afternoon. The technique relies on the fact that applied heat would be carried by flowing water. By applying heat to the basal part of the stem, water flow is inferred from heat flow based on temperature measurements. The simpler method is to determine the rate of heat pulse traveling up the stem by applying pulses of heat at the base and determining the time it takes for the change in temperature to reach a measured distance up the stem from the point of heat application. The measurement yields the velocity of water flow. To obtain the flow rate or quantity of water flow per unit of time, the measurements have to be calibrated against measured rate of transpiration. The method is inaccurate because due to differences in xylem geometry and blockage from plants to plants, the calibration obtained from one plant may not be applicable to another. A better way is based on balancing the heat input to the stem against the heat outflow, yielding directly the rate of flow. The base of the stem is wrapped in an electrical strip heater and the heat input measured in watts. Thermal couples are placed to measure the temperature gradients up and down stream from the heater, and radially across the insulation wrapped outside of the heater. These data, together with thermal conductivity of plant stem and of the heater insulation, are used to calculate with heat transport

equations the heat lost by thermal conduction. The difference between the heat input and loss by thermal conduction indicates the amount of heat transported away from the heater by water flow in the stem. Water flow is then computed from the heat capacity of water and the temperature data.

For the stem flow to be indicative of T of the field, a relatively large number of representative plants must be measured simultaneously. This can be expensive if commercial stem flow gauges are used, especially if the measurement is over many days when stems of the plants are enlarging, necessitating changing over from gauges of one size to gauges of progressively larger sizes.

Soil E and canopy T can also be estimated indirectly. An early method is to sample plants for dry weight and measure ET periodically as the plants grow, and then plot the dry matter produced versus the cumulative ET. Usually the relationship is linear and the line intercepts the ET-axis at a value considerably higher than zero. This intercept value is taken as the total amount of soil E. The underlying assumption is that the amount of dry matter produced at different growth stages of the plant is proportional to the cumulative amount of water transpired up to that time, a fairly reasonable assumption (Fischer and Turner, 1978). Plant T is then the difference between soil E and total ET.

The most obvious indirect way to estimate soil E and canopy T separately is by model simulation. The models are some times very simple but inaccurate. For example, by assuming that soil E declines linearly with time after a soil wetting. More complicated models estimate advective transfer of energy and water vapor between the soil and the canopy environ (e.g., Shuttleworth and Wallace, 1985), but require either simplification of fundamentally complex situations or parameterization for different conditions.

Still another way to estimate canopy T indirectly is to calculate it from measured leaf conductance and leaf area. This involves much uncertainty because the scaling up process, from the leaf level to canopy level, is still experimental and not yet well worked out.

Magnitude of Soil E Relative to ET as Reported in the Literature

In the published studies, soil E was reported to range from a few percent to as much as over 80 percent of the measured or estimated ET. Because of the difficulties encountered in measuring or estimating E and T separately, there is considerable uncertainty in some of the reported results. Nonetheless, some firm data from several studies, together with the relatively consistent conclusions drawn in many other studies of less definitive nature, permit a fairly quantitative assessment. These studies are examined in some detail here, starting with the cases where soil E constituted the major portion of ET and ending with situations where soil E is minimal.

As expected from the previous discussion on factors affecting soil E and plant T, high ratios of E to ET are observed mostly when canopy cover or LAI (leaf area index, leaf area per unit land area) of crop is low and the soil surface is wet or at least not very dry much of the time. Examples are the results obtained by several groups when soil E was measured with microlysimeters under sparse canopies just a day or two after soil surface was wetted. Lascano et al. (1987) found soil E for a cotton field under a LAI of 1.0 to be slightly higher than 5 mm per day on days when ET_o should be in the range of 7 mm per day as judged by the level of solar radiation. Villalobos and Fereres (1990) measured soil E to be 60-80 percent of ET_o for sunflower, maize and cotton with LAI of 0.6 to 1.2. For longer terms but with parts of soil surface drying intermittently, Sadras et al. (1991) found soil E, measured by microlysimeters installed freshly each week, to be 50 percent of ET for two cultivars of sunflowers over a period of 64 days starting

33 days after crop emergence. The plants were spaced widely apart with LAI reaching a maximum of only 1.4 in one cultivar, and 0.9 in the other. Hence, a high proportion of the soil remained exposed for the whole season. The crops were drip-irrigated with 23 to 42 mm of water per week, and there were two rains, of 12 and 8 mm. Presumably a substantial fraction of the soil surface remained wet most of the time. For treatments with irrigation omitted and the soil surface allowed to dry out during either the first half or the second half of the test period, soil E for the 64 days was reduced to 30-35 percent of ET.

Similarly high proportion of soil E was also reported by Lascano and Baumhardt (1996). They used the ENWATBAL model to assess dryland cotton during a period when the LAI started at 0.5-0.9 and reached 1.9 later. There was one furrow irrigation of 100 mm at the beginning of the assessment period and some nine rainfall events totaling 225mm. The simulation daily soil E over a 7-day period after the irrigation was in good agreement with the results measured by microlysimeters (Lascano et al., 1994). For the whole assessment period of 90 days, the simulated soil E was 50 percent of ET.

As the crop canopy covers a greater and greater portion of the ground, soil E becomes less and less. With the exception of crops planted in very widely spaced (e.g., 60 inches or 1.5 m) rows, canopy cover is usually nearly complete (e.g., 95 percent percent) when LAI is 4.5 or higher. In such situations, soil E constitutes a minor portion of ET, even when the soil surface is fully wet. Adams et al. (1976) and Arkin et al. (1974) used arrays of evaporation plates covered with a thin layer of soil to measure soil E after sprinkler irrigations. E of fully wet soil surface as a fraction of ET declined as LAI increased and shading of the soil increased. When the soil was nearly fully shaded, soil E was still 18 percent of the potential value. Jara et al. (1998) combined extensive measurements of T with stem flow gauges, soil E with microlysimeters, and total ET with BREB technique to assess the extent of soil E for maize irrigated by furrow six times during a 64-day period when LAI increased from 3 to 5.2 and then decreased to 4.5. They found daytime soil E, measured by microlysimeters and averaged for 28 days of observation that included up to 6 days after each irrigation, constituted 13.6 percent of daytime ET. But soil E calculated as the difference between ET and T measured by stem flow, averaged over 40 days and including days later than 6 days after an irrigation when the soil surface was drier, constituted only 9 percent of the daytime ET. Although this difference may not all be due to differing soil surface wetness, the data nonetheless show that E was a fairly small fraction of ET when LAI was high. This conclusion is also supported by the results of Bethenod et al. (2000), who studied maize over a 17-day period one year, and a 46-day period the next year. During the study periods, canopy cover of the soil was complete with a LAI of around 4.0. Rainfall, mostly light, was frequent, with the longest dry period being 16 days, and the next longest, 6 days. Overall, the data showed that if soil E was taken as the difference between ET measured by the BREB technique and T measured by stem flow gauges, soil E was approximately 10 percent of the ET.

The higher proportion of soil E under high LAI or canopy cover measured by Arkin et al. (1974) and Adams et al. (1976) in comparison with that measured with microlysimeters and stem flow gauges (Jara et al., 1998; Bethenod et al., 2000) may partly be attributed to the fact that the surface of the evaporation plate used in the former case remained fully wet all the time, whereas in the latter case the soil surface dried out at least to some extent between wettings by rain or irrigation. There might also have been some systematic differences caused by the use of different techniques. Nonetheless, it appears safe to conclude that when canopy cover of the ground is essentially complete, soil E may constitute 10 or 15 percent of ET under normal weather or irrigation conditions with periodic drying of the soil surface, and somewhat more if the soil surface remains fully wet all the time.

Over the full range of canopy cover or LAI, it is desirable to have a function (curve) relating soil E to the LAI or percent of canopy cover. In the literature a number of empirical curves have been constructed from experimental data. Four of them are presented here in Fig. 3. It is seen that generally the curves deviate from each other. The only consistency is that they all show soil E relative to ET or ET_o to decline exponentially with increase in canopy cover or LAI. In considering these curves, it is important to note a number of uncertainties. For one, the soil surface condition may not be as well defined as desired. For example, in the case of Curve (d) obtained by Ritchie and Burnett (1971), soil surface is assumed to be fully wet but in fact could be partially dry because stage 2 evaporation was taken to start after 10 mm of water has evaporated since wetting of the soil whereas their Figure 3 showed stage 2 already started after only 5 mm of water has evaporated. The second uncertainty is that in the case of the relationship with LAI, it will depend on the geometry of plant distribution. The more uniformly the plants are distributed on the land, the more effectively they would shade the soil and reduce soil E. As already mentioned, wide spacing between rows with plants densely spaced along the row will require a higher LAI to shade the same proportion of soil as compared to more narrow distance between rows with plants less densely spaced along the row. Another caveat is that the values are estimates in the case of Curve (d). It was assumed that soil E was equivalent in energy terms to the net radiation measured below canopy when soil surface is wet (Ritchie and Burnett, 1971).

Experimental Studies

As a part of the effort to assess the extent of E relative to ET, to quantify better crop ET and consumptive water use, and to better define the conditions that affect ET, several field studies were carried out in 1999 and 2000 supported by funds from DWR. These studies and the results are described by topics below.

ET of Crops at Two Plant Densities-Indirect Assessment of Soil E

Growing plants at a higher density results in a faster foliage canopy development and more coverage of the soil in the early part of the season. As already discussed, this would reduce the proportion of ET lost by soil evaporation and increase the proportion lost by plant transpiration. Detailed data on ET as affected by plant density are rare. This part of the project is to develop more such data and to assess how much of the soil E may be saved by planting at higher densities.

Methods
The two large (6.1 m diameter) lysimeters at the experimental field of the University of California, Davis were planted on June 4, 1999 with cotton, at a density of 25 plants per m^2 for the weighing lysimeter (WL), and 8 plants per m^2 for the floating lysimeter (FL). The two lysimeters have essentially the same sensitivity and resolution for measuring ET.

A large area surrounding the lysimeters was also planted with cotton of similar density at the same time, to provide adequate fetch or upwind guard area. The lysimeters were routinely irrigated by filling the furrows between beds with water at the time when the surrounding field was furrow-irrigated. However, early in the season the work on the extent ET is suppressed during sprinkler irrigation (see a later section) was also conducted on the lysimeters, entailing the application of water by sprinklers on a number of days. Canopy coverage of the soil was measured periodically by the light interception method with a 1-m long light sensor. ET was monitored over the season by measuring changes in the lysimeter output voltage, calibrated as changes in weight and converted to changes in water content per unit land area. A data logger scanned the output every 1 second, and calculated and stored the mean for each 5 min

interval. The data were downloaded to a computer, adjusted or corrected for the occasional resetting of the sensing mechanism, perturbations caused by persons walking on the lysimeters to take measurements, and irrigations. Daily ET rate was obtained from the adjusted data by summing the 5-min means.

Results and Discussion

The patterns of daily ET for the two densities over the season are presented in Fig. 4, with each sprinkler irrigation (associated with the work of a later section) denoted by an open triangle, and furrow irrigation, by a closed inverted triangle. Also presented in the same figure are the data on canopy cover. Early in the season when the canopy cover was small, each irrigation caused a large increase in ET (irrigation spike) because of wetting of the exposed soil surface. As the soil surface dried over time, soil E decreased fairly rapidly and hence ET also. Later in the season when the canopy covered more of the soil surface, irrigation did not cause sharp increases in ET, and the variation in ET from day to day was caused instead by variations in weather conditions affecting the evaporative demand, as indicated by the ET_o curve (Fig.4c).

Canopy cover developed much faster with the high plant density (WL), reaching 80 percent around 60 DAP (Fig. 4a), whereas with the low plant density (FL) 80 percent cover was not reached until the end of the season (Fig. 4b). Early in the season the base line ET (minimal values between the high ET peaks caused by irrigation) may be taken as a very rough approximation of canopy T. Comparing Fig. 4a and 4b this way, one may surmise that E accounted for a higher proportion of ET at the low plant density (FL). The total ET over the 140-day period was 662 mm for the high plant density and 606 mm for the low plant density, a difference of only 9.2 percent. Dry matter production of plants have been shown to be nearly proportional to the cumulative radiation captured by the plant canopy (Ritchie, 1983). Hence, the relative areas under the canopy cover curves are indicative of the relative total amount of dry matter produced at the two plant densities. On that basis, it may be concluded that for an additional consumptive water use of only 9.2 percent, there was a much larger percentage increase in dry matter produced at the high plant density. That is because a larger proportion of the water used went to soil E in the low density planting compared to the high density planting.

For a more clear cut comparison between two plant densities, we refer to some early data collected with the same lysimeters under another research project (Hsiao and Henderson, 1985) funded by DWR. Beans were planted at two densities, 19 plants m^{-2} in rows spaced normally (normal density), 76 cm apart, and 38 plants m^{-2} in narrow rows 38 cm apart (high density). Irrigation was by sprinkler. The daily ET rates of the two densities are presented in Fig. 5, along with the canopy cover data. As can be seen in Fig. 5, ET rate was higher for the high density planting for the first two thirds of the graph, with most obvious difference in the base line ET. The higher base line ET was associated with the faster canopy development of the high density field. This supports the interpretation that when canopy cover is incomplete, base line ET is mostly due to canopy T when irrigation intervals are long enough to permit the drying of exposed soil surface. After most of the soil is covered by the canopy (day 55 onward), there was very little difference in ET between the two densities. The model of Hsiao and Henderson (1985) that calculated E and T separately was used to simulate the ET of the two densities. As shown in Table 1, the simulated soil E for the low density planting was 101 mm or 28 percent of the total ET for the low density, and 44 mm or 11 percent of the total ET for the high density. The simulated results appear to be realistic in that the simulated total ET for the low and high density were, respectively, 362 mm and 406 mm, values surprisingly close to the measured total ET of 358 mm for the normal and 395 mm for the high density.
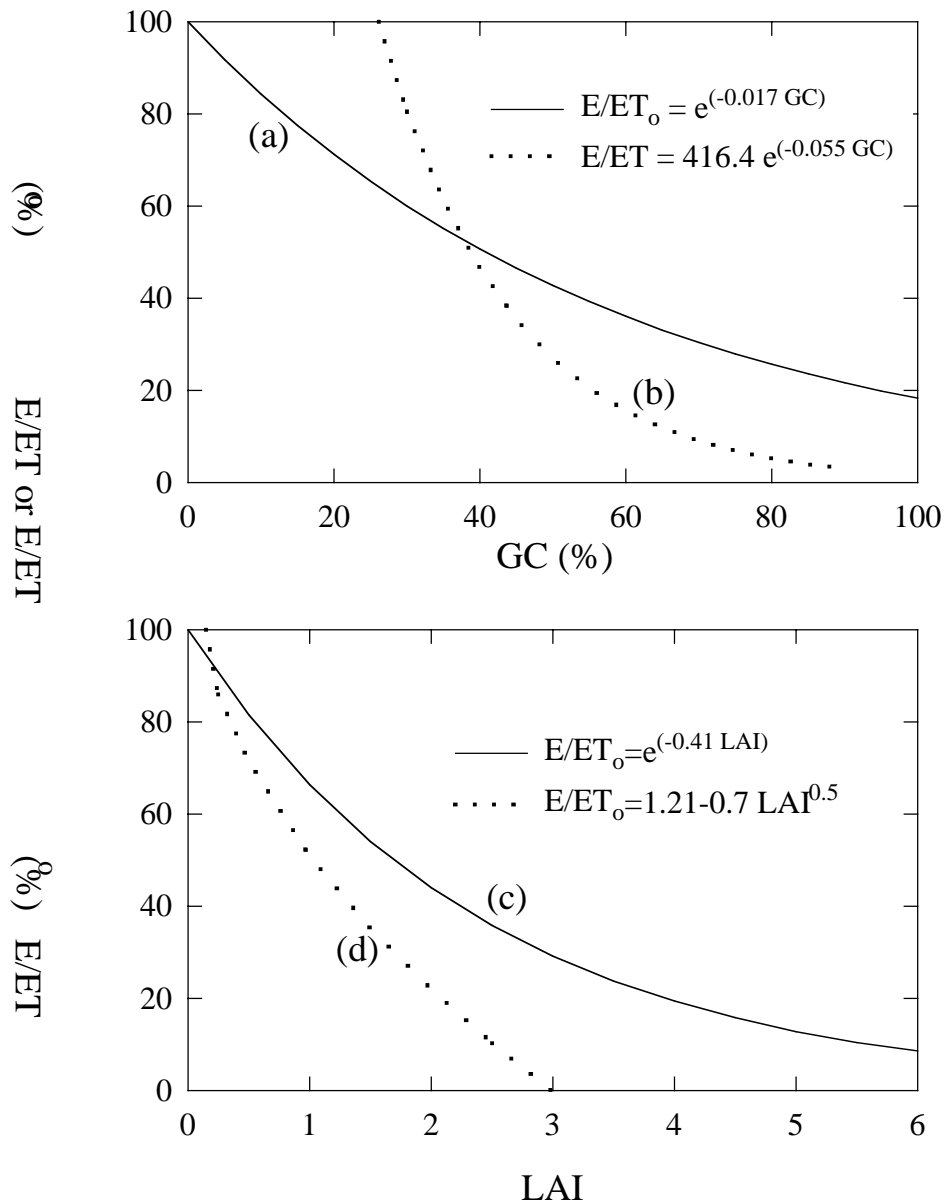
Figure 3. Empirical relationship between ratio of soil E to ET or ET$_o$ and crop canopy cover or LAI. Equations described by the curves are given in the figure. Curve (a) represents the equation of Adams et al. (1975) fitting their experimental data on sorghum, and the equation of Villalobos and Fereres fitting their data on corn, cotton and sunflower; Curve (b) represents an equation fitting the data of Ashktorab et al. (1994) on tomato; Curve (c) represents the equation of Villalobos and Fereres (1991) fitting their data on corn, cotton and sunflower; and Curve (d) represents an equation derived from the equation of Ritchie and Burnett (1971) for T/ET$_o$ vs. LAI fitting their data on cotton and sorghum.
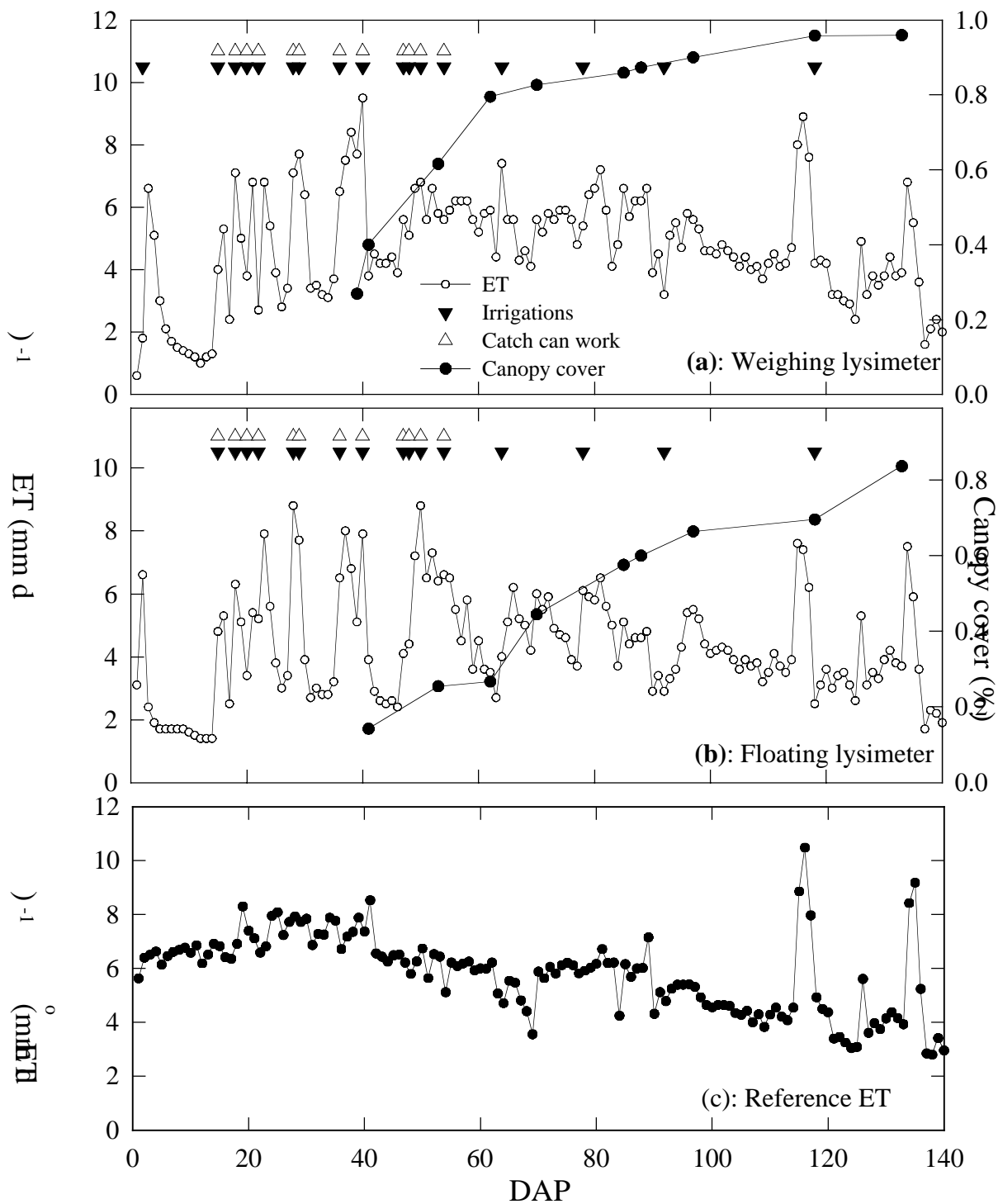
Figure 4. Lysimeter measured ET of cotton planted at two densities, 8 plants m^{-2} for the floating lysimeter (b), and 25 plants m^{-2} for the weighing lysimeter (a). Percentage of canopy cover and ET$_o$ provided by the Davis CIMIS weather station nearby are also shown.

A reasonable conclusion would be that the percentage of ET going to soil E can be reduced substantially by narrower row spacing and higher planting density. On the other hand, this would result in a higher total ET because of the increase in canopy T. Higher canopy T, however, is associated with higher productivity, as already discussed.

Comparison of ET Between Drip and Furrow Irrigated Fields

Drip irrigation is often said to save water because only a portion of the soil surface is wetted at each irrigation. While this is likely true for young orchards with trees spaced far apart and most of the soil not shaded, the validity as a general case may be questioned. This study was conducted to obtain more data bearing on this question.

Methods

Cotton was planted on June 13, 2000 in the two Davis lysimeters and surrounding field at the same density. One lysimeter (FL) and adjacent area was irrigated by a surface drip system, and the other and adjacent area, by furrow irrigation. Weight loss by the lysimeters were monitored to calculate ET rate; and canopy cover on each lysimeter was measured periodically. During the early phase of growth, plants on the FL were less green and grew slower than plants on the WL and surrounding area. Tests indicated that the soil of the FL was slightly more saline and basic than the soil of the WL. Extra water was applied at irrigation time the FL to leach the soil and reduce the salinity. The FL plants soon recovered and started to grow normally. To account for the difference in canopy cover, an adjustment in the ET data was made. The excessive canopy cover of the WL (in percentage), calculated by subtracting the canopy cover on the FL from that on the WL, was divided by 100 and multiplied by an assumed crop coefficient of 1.1, and the result was added to the measured ET of the FL.

Results and Discussion

The rate of daily ET under drip and furrow irrigation as measured by the lysimeters are given in Fig. 6, along with the data on canopy cover. Because of the salinity problem with the FL, there was a substantial difference in canopy cover between the two irrigation methods in the first part of the season and it was desirable to adjust the ET data for the difference in canopy sizes as described under *methods*. The adjusted ET data are presented in Fig. 6c. It is seen in Fig. 6a and 6c that the most obvious difference in ET between the drip and furrow irrigated lysimeter in the first 50 days is the lack of irrigation spikes in the former and the prominence of irrigation spikes in the latter. In addition, not as obvious but still clear is the higher ET of the drip irrigated lysimeter starting several days after one furrow irrigation and lasting until the next furrow irrigation. These differences are the result of fundamental differences in the two water application methods. With furrow irrigation, the spikes and the rapid decline are caused by the sudden wetting of the whole soil surface, followed by surface drying and stage 2 exponentially declining evaporation rate from exposed soil surface. With drip irrigation, only a portion of the exposed soil surface is wetted at each irrigation but this portion stays fully or fairly wet most of the time due to the short time intervals between irrigations. Hence, during the time when the furrow irrigated soil surface had dried out enough to limit soil E markedly, the ET of furrow irrigated lysimeter is less than the ET of the drip irrigated one because the latter has a part of its soil surface still wet.
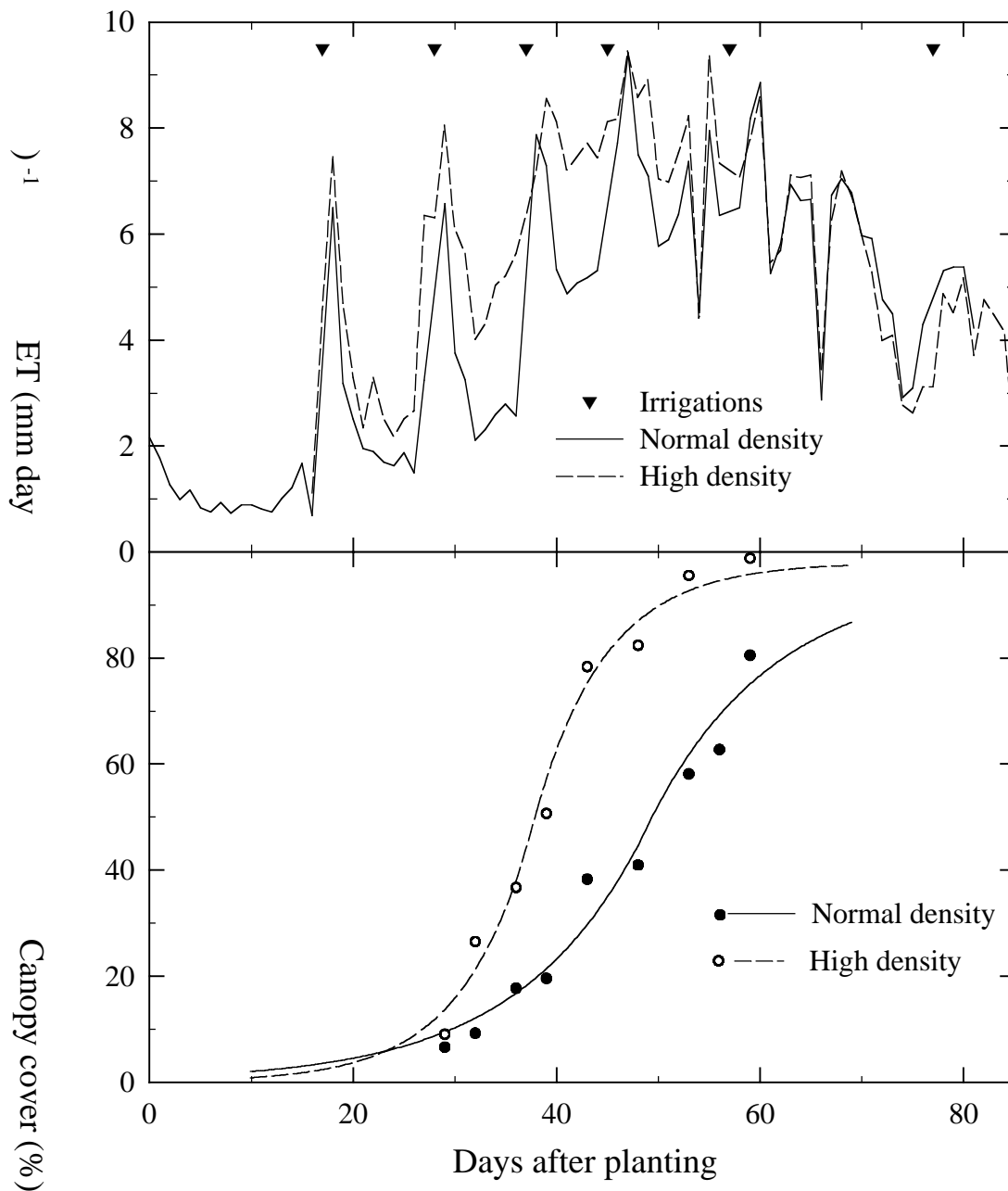
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Figure 5. Evapotranspiration and canopy cover of bean planted at two densities, 19 plants m^{-2} (normal, with 76 cm row spacing) and 38 plant m^{-2}.(high, with 38 cam row spacing). Inverted solid triangles indicate sprinkler irrigations. Measured canopy cover is given as circles; lines are fitted using the canopy growth model of Hsiao and Henderson (1985). Same experiment as that shown in Fig. 1.

Table 1. Cumulative soil E and canopy T and ET as predicted by the model of Hsiao and Henderson (1985) in comparison with cumulative ET as measured by lysimeters, for fields of beans planted at two different densities. Data are for a period of 79 days starting 1 day after planting.

	Plant Density			
	19 plants m^{-2}		38 plants m^{-2}	
	(mm)	(% of ET)	(mm)	(% of ET)
	Model			
Soil E	101	28	44	11
Crop T	261	72	362	89
ET	362	100	406	100
	Measurement			
ET	358	----	395	----

Over the period of 90 some days, the measured total ET was 436 mm for the furrow irrigated (WL), and 387 mm for the drip irrigated (FL). After adjusting for the difference in canopy cover (see *Methods*), the total ET for the drip irrigated was 426 mm. Assuming the adjustment is reasonable, the similarity in total ET between the furrow and drip irrigated cotton indicates that drip irrigation does not necessarily save water in some situations. This conclusion is consistent with those drawn in several other careful studies (e.g., Tarantino et al., 1982). In the current study, the frequent wetting of a part of the soil by drip irrigation kept the ET high during the periods when ET of furrow irrigated treatment was low due to soil surface drying over the long intervals between irrigations.

Extent crop ET is Suppressed During Sprinkler Irigation.

Sprinkler irrigation is sometimes said to be wasteful because after being emitted by the sprinklers, the water drops evaporate partly in the air before reaching the soil and the crop. In terms of the energy balance principle, however, in-air evaporation from the water drops should reduce the energy supply to the field and cool and humidify the air, leading to reduced rate of ET from the soil and the crop. This study was conducted to quantify the extent surface ET is suppressed during sprinkler irrigation.

Methods

The two lysimeters were planted with cotton in 1999 and 2000. To determine the extent ET is suppressed, the normal rate of ET (control) without sprinkling must be known, and one lysimeter (FL) was used for this purpose. The other lysimeter (WL) was used to determine the ET rate under sprinkler application. To measure ET from the soil/crop surface during sprinkler application, the amount of water applied and reaching the surface must be accurately measured and deducted from the change in weight of the lysimeter. Sixty small platforms each with three supporting legs were distributed on the lysimeter. A catch can was placed on each platform and carefully leveled with a spirit level. A layer of oil about 1 cm thick was added to the can to prevent evaporation of water caught in the can. The can with its content was weighed before and after the sprinkler application, to 0.1 g accuracy, to determined the depth of water applied. Tests conducted with cans containing water dyed brightly red and placed on white paper sheets showed that there was no detectable splatter from the can during sprinkling. After adding water to cans containing oil, weight of the cans did not change significantly after sitting in the field for a number of hours, indicating no evaporative loss. For each test run, the FL was irrigated by sprinkler to ensure that its top soil layer is fully wet. The irrigation was stopped just before applying water to the WL (equipped with

catch cans) by sprinklers. The reported rate of ET measured by the WL has been corrected for the surface area occupied by the non-evaporating catch cans.

Results and Discussion

Figaure 7 shows an example of the change in weight of the two lysimeters with time during the test. The continuous gain in weight for FL between 11:20 and 14:00 was the result of water application by sprinklers. After the application was stopped, the continuous loss in weight of FL with time was due to ET. At about 14:05 the sprinklers were turned on to apply water to the WL, which gained weight continuously until the application stopped at 16:30. The water applied as measured by the catch cans minus the water gained by the lysimeter between 14:05 and 16:30 was taken as the cumulative ET from the WL during the sprinkler application.
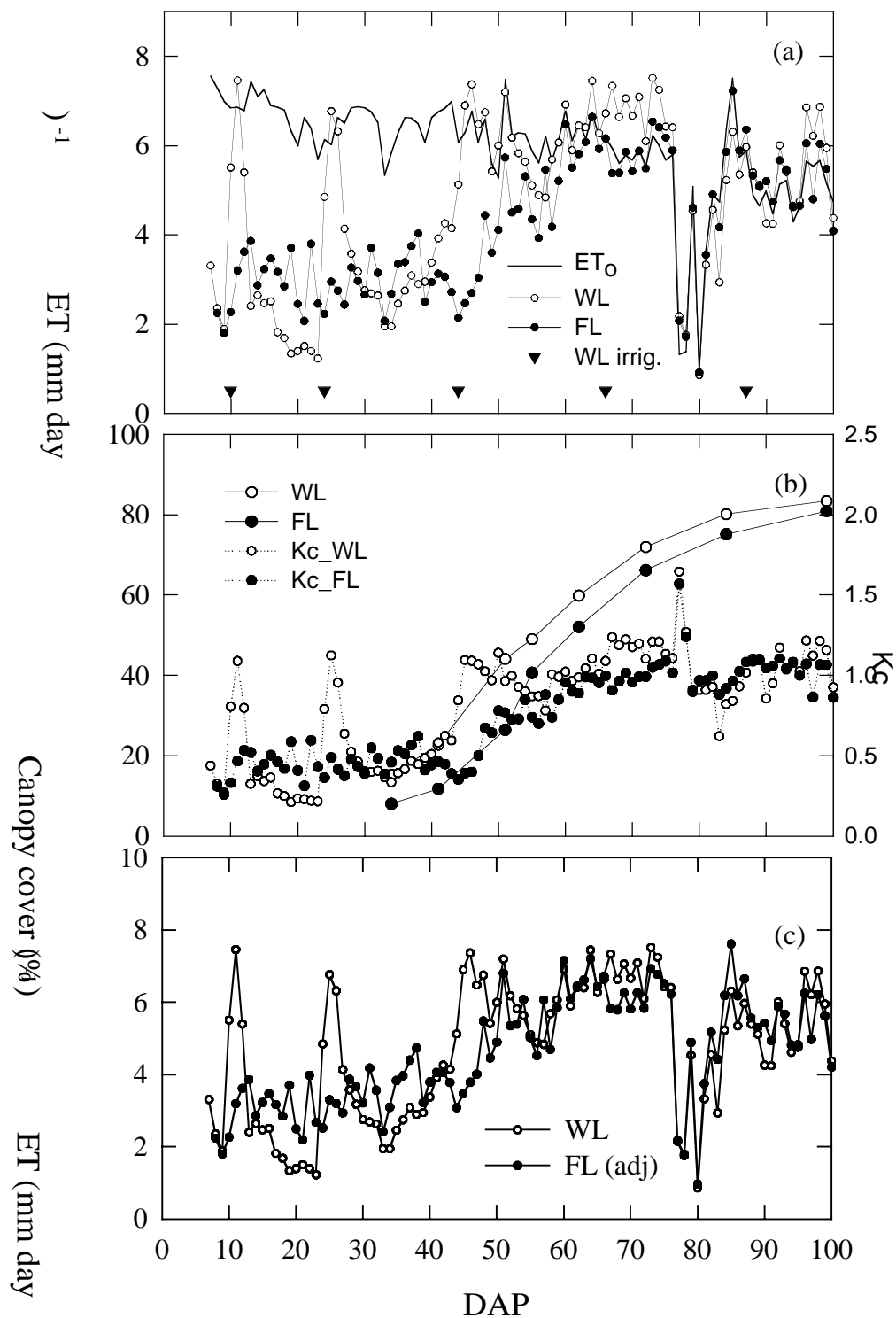
Figure 6. Trend of daily ET, ET$_o$, canopy cover, and daily crop coefficient (K$_c$) for cotton under drip irrigation (floating lysimeter-FL) or furrow irrigation (weighing lysimeter-WL). Comparison of crop ET for the two irrigation methods after adjusting for the effect of the lower canopy of the drip irrigated (see *Methods*) is given in (c). Downward triangles indicate the time of furrow irrigation. Planting was on June 13, 2000.
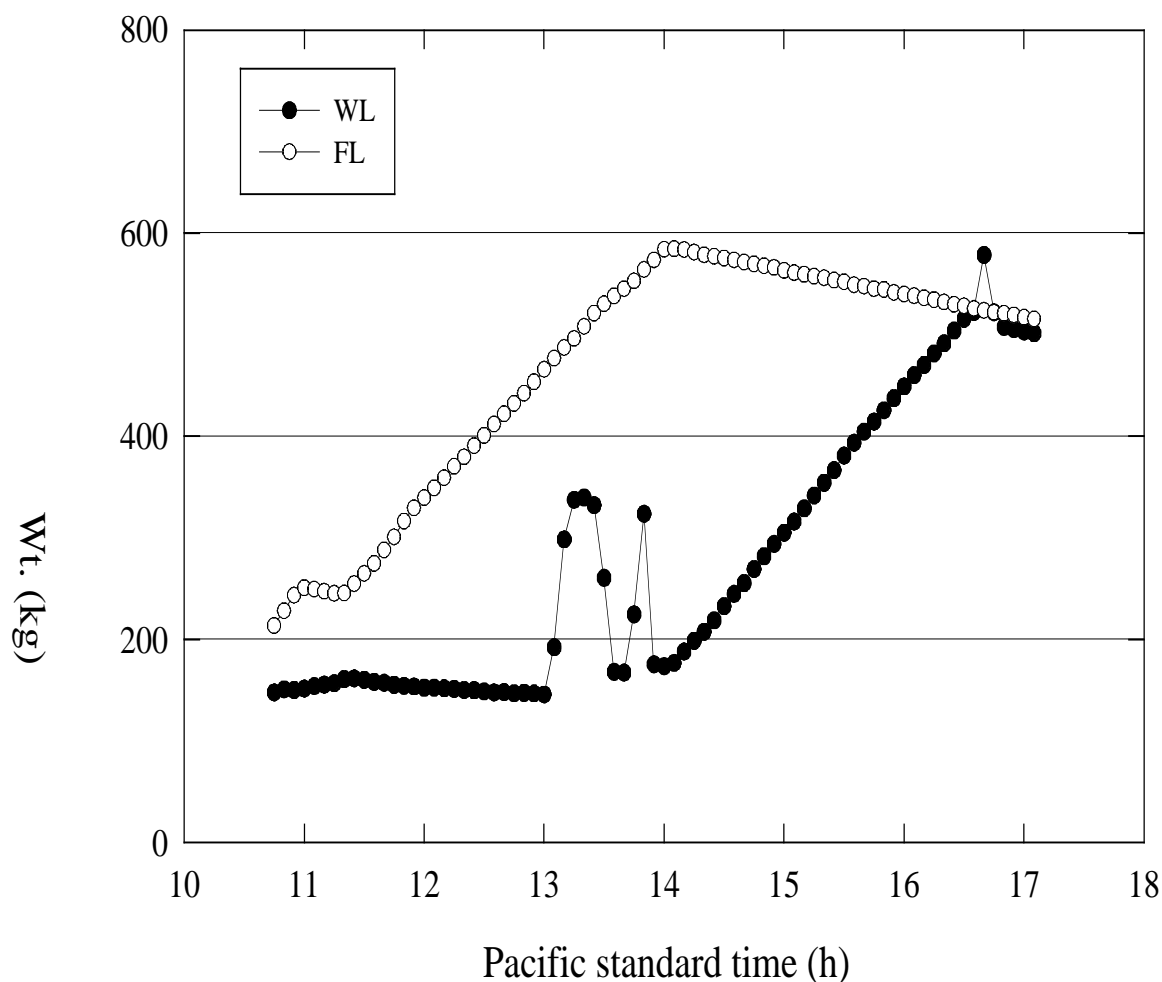
Figure 7. Example of weight change of the weighing and floating lysimeters during the determination of surface ET while under sprinkler irrigation. Weight was measured from an arbitrary reference point and was not the total weight of the lysimeter. The rapid changes in weight between 13:00 and 14:00 were due to weight of the researchers setting up the catch cans, and around 16:45, weight of the researcher taking away the cans for weighing.

Of the total eight tests conducted in 1999, three of them gave unacceptable values of ET under sprinkler irrigation, either much higher than the control ET and ET_o, or negative values. The results of the remaining five tests and the four tests conducted in 2000 the mean values are presented in Table 2. As can be seen, the variation from test to test was large and less definitive than we had hoped for. It can be seen from the slopes of the lines in Fig. 7 and in Table 2 that ET during sprinkler application is very small relative to the application rate, and hence, relatively small errors in the amount of applied water measured by catch cans can lead to a large error in the calculated ET under sprinkling.

The reduction in ET under sprinkling as a percentage of the control ET was calculated for each test and given in Table 2. For the 1999 tests, the mean percentage reduction was 48 percent, and for 2000, the mean was 46 percent. The overall mean reduction was 47 percent for the nine tests in two years. A

reasonable conclusion would be that during water application by impulse sprinklers, surface ET is substantially suppressed, although in-air evaporation of the spraying water drops probably makes up for the difference and more.

Table 2. ET rate of a cotton field under sprinkler irrigation relative to ET rate not under irrigation (control ET). Reduction of ET rate under sprinkling is given as a percentage of the control ET rate. Control lysimeter was irrigated by sprinklers first, then the sprinklers were turned off at the start of the ET measurement. ET rate was calculated as the difference between the water application rate measured by catch cans and the water gain rate measured by lysimeter.

Date	Time (Pacific standard)	ET_o (mm h^{-1})	Lysim. water gain rate (mm h^{-1})	Water appl. rate (mm h^{-1})	Control ET (mm h^{-1})	ET under sprinkler (mm h^{-1})	ET reduction under sprinkler (%)
Year 1999							
6/18	14:00-16:30	0.65	4.79	4.96	0.80	0.17	79
6/21	11:00-14:00	0.72	4.74	5.40	0.85	0.65	24
7/1	12:00-14:30	0.82	4.92	5.48	0.93	0.56	40
7/2	11:00-13:00	0.80	5.01	5.60	0.89	0.59	34
7/20	12:40-15:10	0.70	5.72	6.00	0.76	0.28	63
Year 2000							
10/3	11:00-14:00	0.510	6.46	6.86	0.55	0.41	26
10/6	10:50-13:50	0.58	6.06	6.42	0.66	0.37	44
10/13	10:30-13:30	0.38	7.05	7.10	0.37	0.051	86
10/19	12:00-15:00	0.38	6.54	6.84	0.42	0.31	26
2 year mean							47

Extent Transpiration May Increase When Soil Evaporation is Minimized

One idea for saving water is to minimize or eliminate soil E while not restricting crop T. During the early part of the life cycle of crops, only a part of the soil is covered by the foliage canopy and soil E is high if the soil surface is wet. If soil E is reduced, less energy is consumed by soil evaporation and air above and near the soil would be less humid and hotter. This in turn causes the canopy to be hotter and surrounding air to be less humid. T would increase as the result of a large humidity gradient (ΔW) from the leaf to the air. Very little work has been done to quantify this effect by experimental measurements. This study was conducted to develop some of the needed information. The objective is to measure the increase in canopy temperature and the reduction in air humidity and use the data to calculate how much T would be raised by the reduction in soil E.

Methods

In a large field of cotton two adjacent plots, 15x15 m each, were demarcated. The plots were irrigated once or twice to establish the plant stand. On day 35 after planting in 1999, and day 44 after planting in 2000, irrigation began to be applied to the WET treatment every 14 to 20 days, while DRY treatment received none. Temperature of 18 mature leaves on top of the canopy in each plot was measured continuously with fine-wire (40 gauge) thermocouples attached on the lower side of the leaf. The thermocouples were checked every morning, and if they fell off the leaf, the readings back to the previous morning were excluded in the calculation of leaf temperature averaged over all the measured leaves. Vapor pressure inside the leaf was calculated from leaf temperature by assuming vapor saturation. This assumption has been shown to be valid by experiments and is used regularly in all published gas exchange studies. Water vapor pressure and temperature of the air 0.1 m above the canopy of each plot were measured with a precision psychrometer (Held et al., 1990), positioned at the center of each plot to avoid edge effects. Voltage outputs from the thermocouples and psychrometers were scanned every 1 second and averaged every 5 min by a data logger, and the means values stored.

The driving force for transpiration, the difference in vapor pressure between inside of the leaf and the bulk air surrounding the canopy (ΔW), was calculated from the calculated vapor pressure inside the leaf and the measured vapor pressure in the bulk air. To assess the impact of reduced soil E on canopy T, we assumed that the stomatal conductance are basically the same for the plants in the WET and DRY plot and the only effects on canopy T are those due to changes in temperature and humidity (vapor pressure), which alter ΔW. Since the rate of transpiration is proportional to ΔW for a given conductance, the increase in canopy T of the DRY plot due to the dry soil surface should be proportional to the increase in ΔW. That is, the percentage increase in T is the same as the percentage increase in ΔW. Using this approach, the increase in canopy T was calculated and added to the estimate T of the WET plot to obtain T of the DRY plot. Canopy T of the WET plot was estimated using our ET model (Hsiao and Henderson, 1985).

Vapor pressure at and temperature of the soil surface at random locations in the plots were measured periodically with a special instrument (Seymour and Hsiao, 1984). Air humidity at about 1 m height was also measured at the same time with the same instrument.

Results and Discussion

In both years soil surface vapor pressure increased markedly after each irrigation, then declined with time and became nearly the same as air vapor pressure after 10 days to 2 weeks. The data obtained in 2000 are given in Fig. 8. Very similar but less complete data (not shown) were obtained in 1999. Since vapor pressure of the soil surface and of the air became very similar at that time, soil E should be rather insignificant 10 days to 2 weeks after an irrigation.

The driving force for transpiration (ΔW) was calculated. Samples of the results in 1999 are given in Fig. 9 for two dates before an irrigation, the day of irrigation and the three days after the irrigation. It is seen in Fig. 9 that before the irrigation, ΔW was similar for much of the time each day between the WET and DRY plots, with ΔW for the DRY plots often slightly lower than that for the WET early in the afternoon. After the soil surface was wetted by the irrigation at 11:00 on July 23, ΔW became markedly smaller for the WET plot from in the morning. Six days after the irrigation, the difference in ΔW between the two treatments became much less.
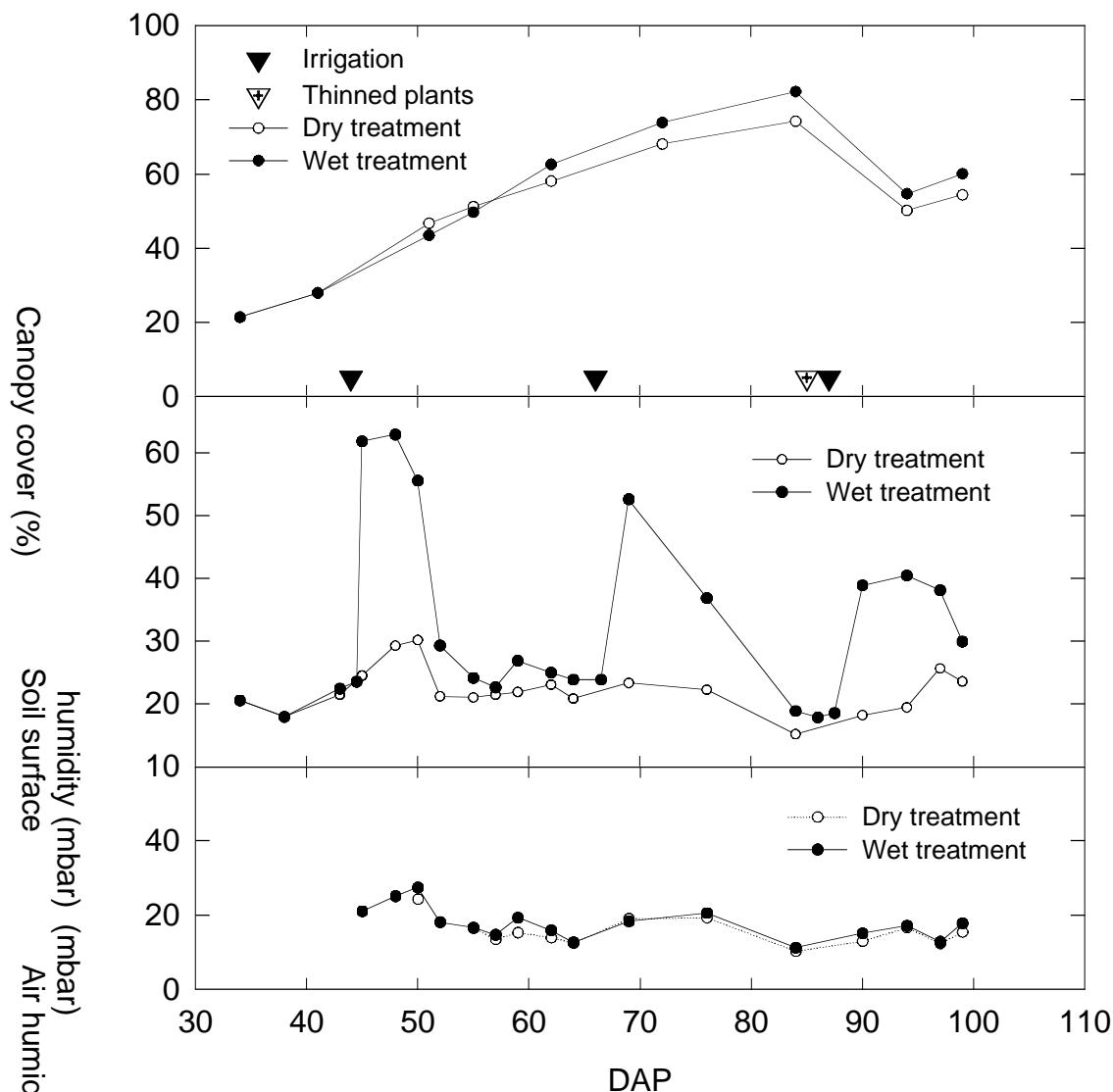
Figure 8. Absolute humidity (vapor pressure) of the exposed soil surface and of the air for the Wet treatment as affected by furrow irrigation (inverted solid triangles), and for the Dry treatment not receiving irrigation. Canopy cover of each treatment are also shown. On 85 DAP, the plant was thinned to about 2.5 plants m^{-2} to reduce the canopy cover in order to have a higher proportion of exposed soil surface.

The 2000 data of ΔW are presented as midday mean over a test period of over 70 days in Fig. 10. In the lower part of the figure the ratio of ΔW of the Dry treatment to ΔW of the wet treatment is shown. It is seen that this ratio increased substantially after each furrow irrigation, then declined over a period of several days to one week to a base value of 1.0.

Throughout the experiments in 1999 and 2000, there was no significant water stress in the plants of the DRY plot, as indicated by the absence of stress symptoms and a canopy size nearly the same as the WET

plot. That is due to the high water holding capacity of the deep Yolo loam soil at the experiment site, and fast development of the root system of many crops including cotton on this soil.

Using the estimated ΔW, the increase in canopy transpiration (T) caused by dry soil surface was calculated for the midday period over two irrigation cycles in 1999, and the results are presented in Fig. 11. Both treatments were irrigated the same way on 35 DAP and canopy T was similar for the WET and the DRY plots and the canopy cover was also similar. As expected, irrigation of the WET plot on 49 DAP caused a large difference in canopy T between the WET and DRY plots. This difference lessened gradually over time and became insignificant after about a week. The canopy grew from approximately 30 percent coverage of the soil at 49 DAP to 60 percent coverage of the soil on 63 DAP. The next irrigation of the WET plot, applied on 63 DAP, had no significant effect on canopy T. Most likely that was due to the fact that by then the canopy covered more than 60 percent of the soil, and heating of the small portion of the dry soil surface was insufficient to have a measurable effect on canopy temperature. Therefore the estimated canopy T was essentially not affected. Overall, compared to the intermittently wetted soil surface, dry soil surface was estimated to increase canopy transpiration by 17 percent over the 15 days of testing period (49 to 63 DAP).
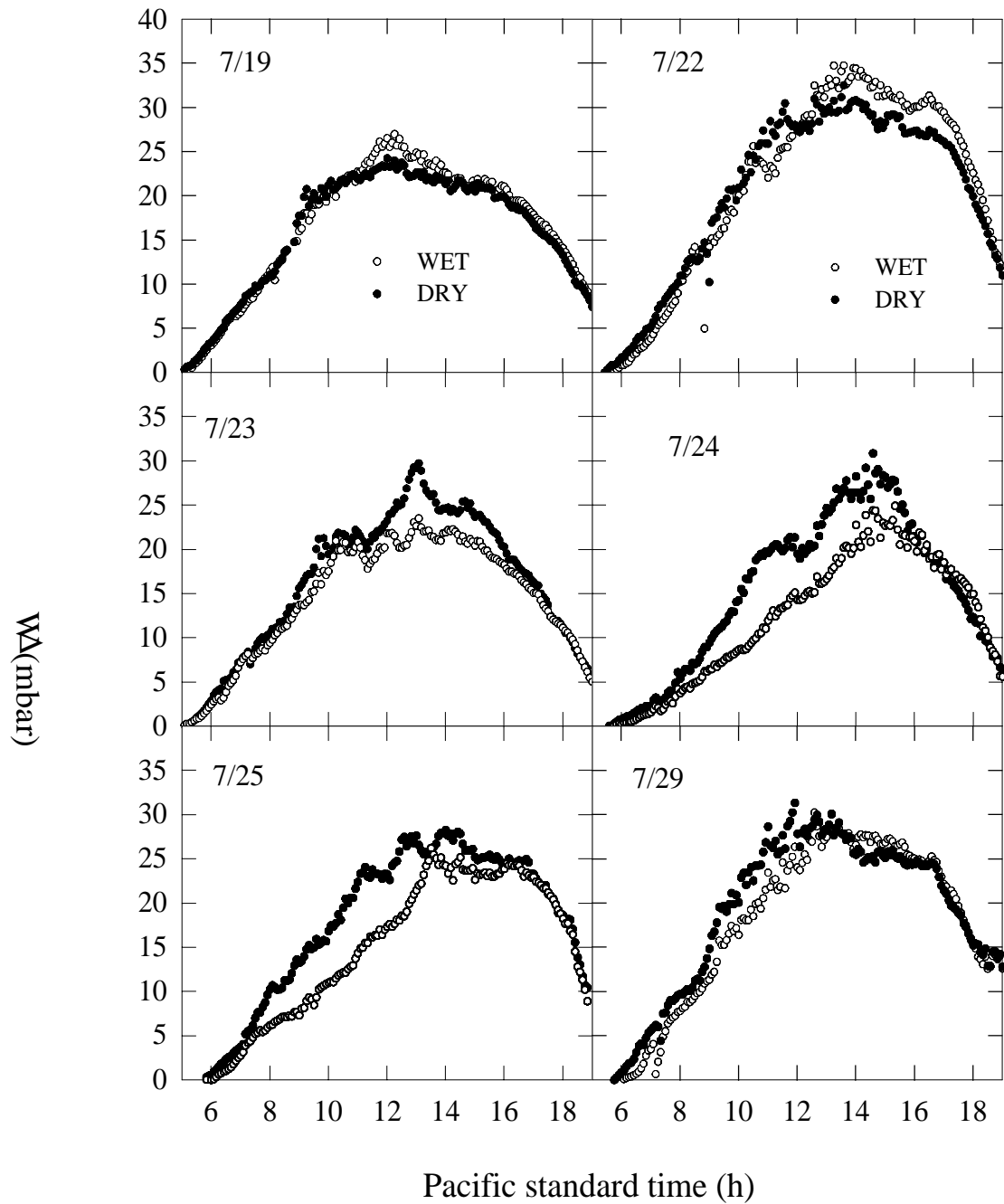
Figure 9. Vapor pressure difference (ΔW) between the interior of leaves and the air for cotton in the WET and DRY treatments on six dates in 1999. Irrigation of the WET plot was on 7/23 starting about 11:00.

It should be pointed out that the above estimates of the potential increase in canopy T are likely to be on the high side. The estimate was based on midday data, when intrarow advective effect is expected to be the greatest. Basing the estimate on the cumulative daily data would have reduced the estimate enhancement in canopy T. Also, in estimating canopy T the DRY plants were assumed to have the same canopy conductance as the WET plants. In reality, conductance was probably lower for the DRY than the WET plants because cotton stomata close more as ΔW increases (Xu, 2000), and therefore canopy T would not have been enhanced as much.

The results in both 1999 and 2000 indicate that eliminating or markedly reducing soil E would enhance canopy T significantly only when canopy coverage of the ground is small, and the effect is only substantial in the first several days after an irrigation. Thus, unless the soil surface is wetted by irrigation very frequently when canopy cover is small, the increase in canopy T for the season by eliminating the wetting of soil surface is likely to be minor.

General Discussion and Conclusion

This chapter is based both on a study of the literature and on substantial experimental work conducted at the University of California, Davis, over two years. The review of literature confirms what is generally, if vaguely, taken for granted. That is: when crop canopy cover of the soil is partial, canopy T is less than the rate of ET_o, and soil E is substantial when the soil surface is wet and exposed, and decreases as canopy cover increases. Although the number of reasonably definitive studies is limited, the results are fairly consistent and shows (Fig. 3) that when canopy cover of the soil is partial and soil surface wet, canopy T as a fraction of ET is not just proportional to the fractional canopy cover but greater; and soil E as a fraction of ET is not proportional to the fractional exposed soil surface but less. In other words, canopy appears to exert a disproportionately large impact on canopy T and on soil E. On the other hand, when canopy coverage of the soil is complete or very nearly so, there is still some soil E, in the order of 10 percent or less of ET.

Once the exposed soil surface begins to dry, soil E declines exponentially with time and the empirical data indicate that canopy T increases at least slightly as the result. This point is emphasized in the analysis by Ritchie (1983), of canopy T as a fraction of ET in relation to LAI. Nonetheless, the conclusion is not as firm as one would like because it is based on comparing T/ET data measured or estimated with different methods from different studies.

The experimental work conducted at Davis demonstrates clearly the influence of plant density on the speed of canopy development and hence on the extent of soil E relative to canopy T. Higher plant density and more canopy cover reduce soil E but increase canopy T. Consequently the total ET is usually increased but the amount of soil E is reduced, as demonstrated in Fig. 3 and 5. The increase in total ET caused by increased canopy T is beneficial, in that more biomass is produced by the crop per unit of ET. That is, the efficiency of consumptive water use for biomass production is improved.
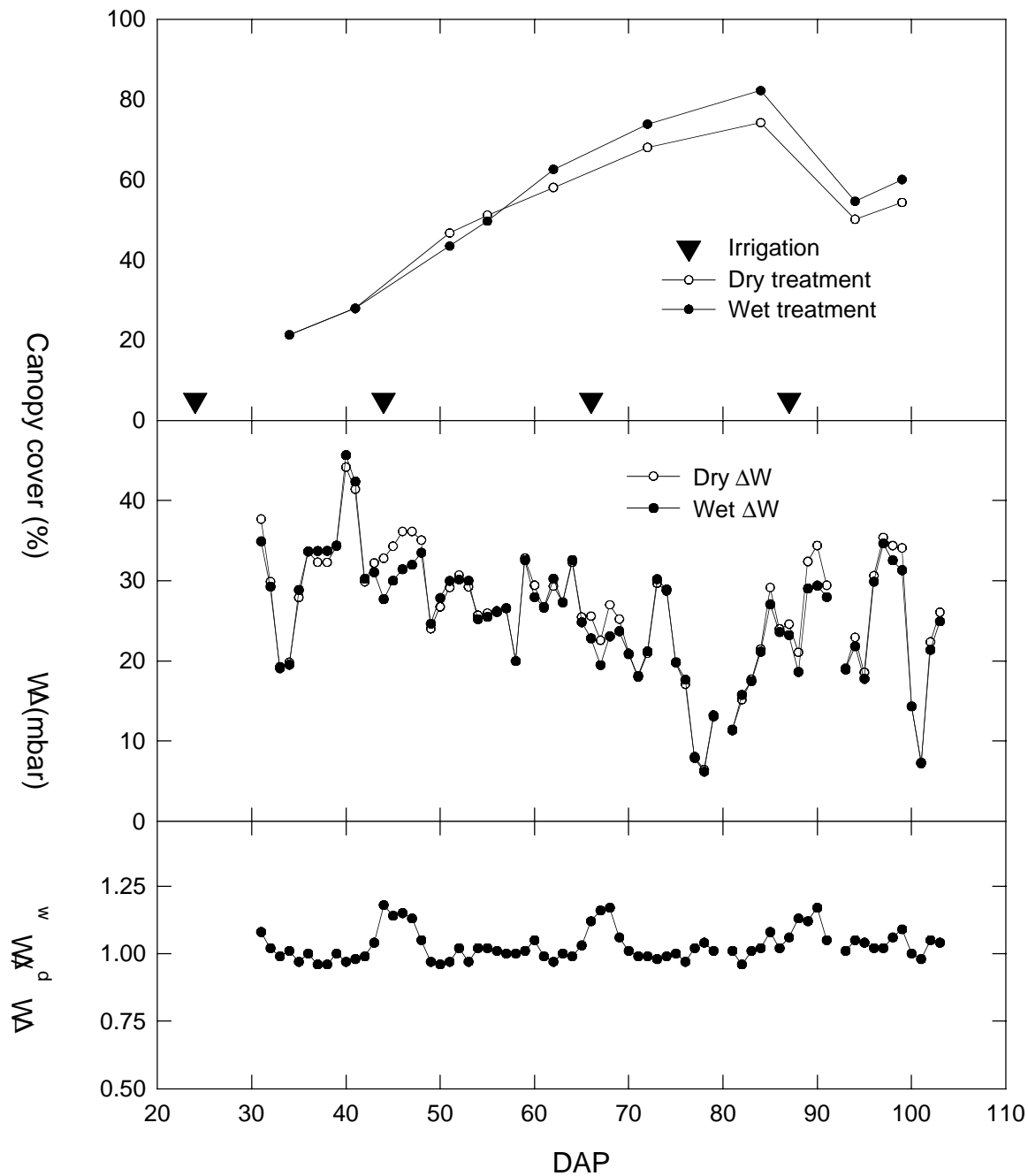
Figure 10. Difference in midday (11:30 to 12:30 PST) water vapor pressure (ΔW) between the foliage interior and the bulk air for the Dry and Wet cotton in 2000, and the ratio of ΔW for the Dry treatment to ΔW for the Wet treatment. Irrigation (inverted arrow heads) on 24 DAP was applied to both treatments, but subsequently only to the Wet treatment. On 85 DAP, the stand was thinned to 2.5 plants m^{-2}. ΔW was calculated from foliage temperature and bulk air vapor pressure.

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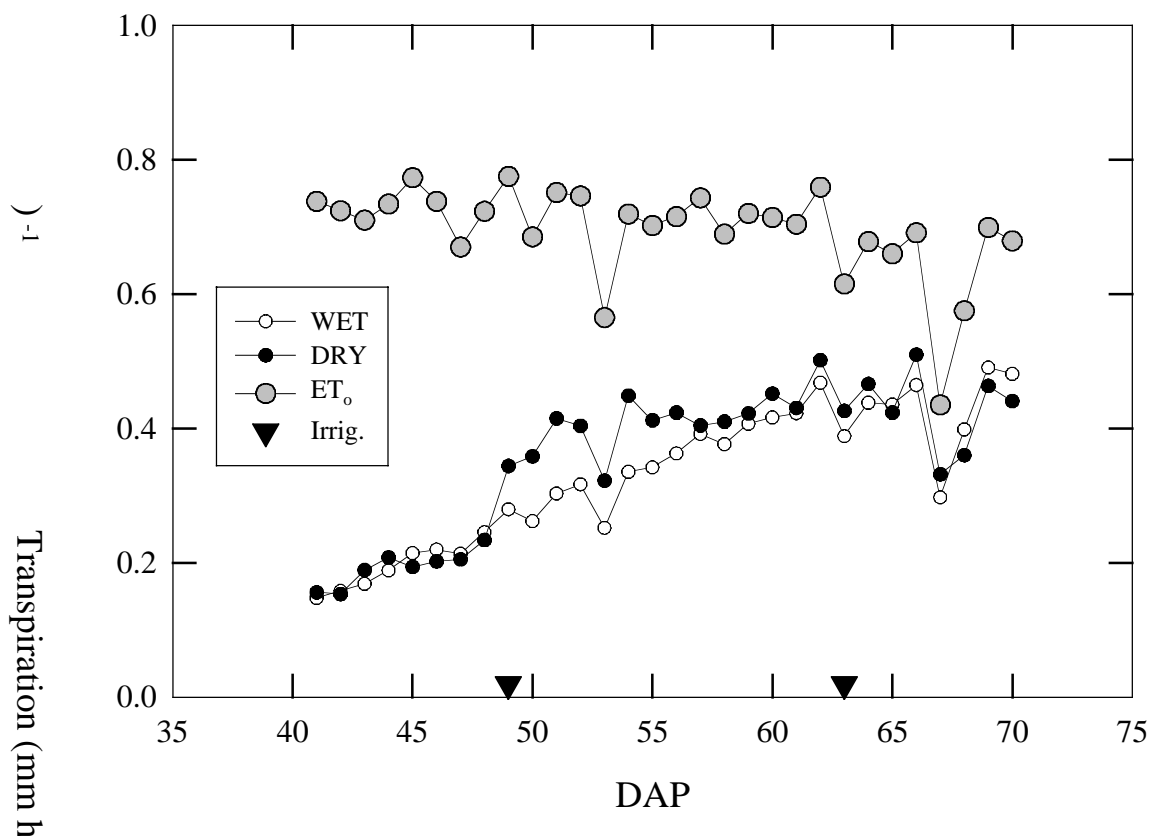
Figure 11. Calculated effect of soil drying on canopy transpiration for the midday period of 11:30 to 12:30. Solid and open symbols are for DRY and WET treatments, respectively. Inverted triangles indicate the time of irrigation of the WET treatment. Transpiration was calculated using ΔW data as indicated in the text.

Another aspect of the experimental work compared ET of cotton irrigated by drip with that irrigated by furrow. Without irrigation ET spikes, the pattern of daily ET over time for the drip irrigated is very different from that for the furrow irrigated (Fig. 6a). For cumulative ET over the experimental period, the data are not totally conclusive because the lysimeter of the drip irrigated treatment developed a salinity problem that slowed the growth of cotton before it was corrected. Minor adjustment of the ET data were made to account for this difference in canopy cover. Cumulative ET calculated from the adjusted data (Fig. 6c) indicates that consumptive water use of the drip irrigated treatment was essentially the same as that of the furrow irrigated treatment (436 mm vs. 426 mm). These results support the conclusions drawn in several other studies (e.g., Tarantino et al., 1982) that drip irrigation may not reduce soil E under some conditions. Drip irrigation is likely to reduce ET through the reduction in soil E in comparison to surface irrigation if one or more of the following conditions apply: (a) the time interval between drip irrigations is longer than that used in this study; (b) the time interval between furrow irrigations is shorter than that used in this study; and (c) the canopy cover develops more slowly (e.g., by planting at a lower density or by being deficient in mineral nutrients, or growing a species of crop with a slower growth rate) than that observed in this study. It is obvious that a number of other factors such as soil water holding capacity,

rooting depth, and sensitivity of the crop to low soil water status enter into consideration when deciding on irrigation intervals in addition to the potential reduction in soil E.

The extent that ET from the soil and from the crop is suppressed during sprinkler water application was also carefully assesses in many tests over the two year period in Davis. ET rate had to be calculated as the difference between the water application rate as measured by catch cans and the rate of water gain by the field as measured by precision lysimeters. Due to the fact that ET rate is small when compared to the rate of water application by impulse sprinklers, the results are quite variable. By conducting a total of nine successful tests, it is possible to conclude that ET is suppressed during the time of sprinkler irrigation, by probably 40 to 50 percent in comparison to ET from a wet field without the sprinkling. The suppression is the result of the spraying water drops from the sprinklers humidifying and cooling the air. Thus, the in-air evaporation from the falling water drops is not all vain, in that some saving of ET results. The saving is not greater because rotation of the sprinkler heads places the spray over a particular area only periodically. The general impression is that sprinkler irrigation involves extra water loss due to in-air evaporation of the drops. The extent of this evaporation has been calculated in a theoretical way, based on drop size distribution, traveling distance, and wet bulb depression as a function of air humidity. This effort should be expanded and combined with experimental measurements to better assess the in-air evaporation of sprinkler systems. The in-air evaporation rate can then be compared with the extent of ET suppression to ascertain just how much extra water is lost during sprinkler irrigations.

The final part of the experimental work was to estimate the potential increase of canopy transpiration if soil evaporation is greatly reduced or eliminated. This was done by measuring increases in foliage temperature when soil surface was dry compared to when it was wet, under conditions when canopy covered the soil only partly. Using the fact that leaf interior is essentially saturated with water vapor and the well know saturation vapor pressure vs. temperature curve, the potential effect on transpiration was estimated from the increases in water vapor gradient from the foliage to the bulk air driving transpiration. The results show that in the worst case scenario, canopy T over a dry soil surface may be 30 percent higher than over a fully wet soil surface, and the difference narrows and became insignificant as the soil surface dries over time. The common time interval between surface irrigations is in terms of a week to many days, ample time for the drying of exposed soil surface. Hence, when averaged over a period of weeks or more the difference in canopy T over a dry soil compared to a soil wetted periodically by irrigation should be considerably less. In the case we evaluated, the average difference was 17 percent for a period when the canopy cover was low. Generally speaking then, there would be some increase in canopy T when canopy cover is incomplete if soil E is essentially eliminated by irrigating with buried drip systems. The elimination of soil E, however should still result in a significant saving in total ET or consumptive water use.

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SIMETAW
(Simulation of Evapotranspiration of Applied Water)

The SIMETAW program was developed to simulate weather data from monthly climate data and to estimate reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) with the simulated data. In addition, simulated daily rainfall, soil water holding charactersistics, effective rooting depths, and ET_c are used to determine effective rainfall and to generate hypothetical irrigation schedules to estimate the seasonal and annual evapotranspiration of applied water (ET_{aw}), where ET_{aw} is an estimate of the crop evapotranspiration minus any water supplied by effective rainfall. The simulation program allows one to investigate how climate change might affect the water demand in California. All of the ET_{aw} calculations are done on a daily basis, so the estimation of effective rainfall and, hence, ET_{aw} is greatly improved over earlier methods. In addition, the use of the widely adopted Penman-Monteith equation for reference evapotranspiration (ET_o) and improved methodology to apply crop coefficients for estimating crop evapotranspiration is used to improve ET_{aw} accuracy.

Methodology

Weather Simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop responses to environmental conditions. One important response is crop evapotranspiration (ET_c). Crop evapotranspiration is commonly estimated by multiplying reference evapotranspiration by a crop coefficient. In SIMETAW, daily data are used to estimate reference evapotranspiration. Rainfall data are then used with estimates of ET_c to determine ET_{aw}. One can either use raw or simulated daily data for the calculations.

Rainfall

Characteristics and patterns of rainfall are highly seasonal and localized, so a making a general, seasonal model that is applicable to all locations is difficult. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that the rain status of previous day tends to affect present day's condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform [1–4]. This approach consists of two models: two-state, first order Markov chain and a gamma distribution function. These models require long-term daily rainfall data to estimate model parameters. SIMETAW however, uses monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models.

Wind Speed

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function, as described for rainfall. While using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to have some unrealistically high wind speed values generated for use in ET_o calculations. Because wind speed depends on atmospheric pressure gradients, no correlation between wind speed and the other weather parameters used to estimate ET_o exists. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high ET_o estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at

twice the mean wind speed. This is believed to be a reasonable upper limit for a weather generator used to estimate ET_o because extreme wind speed values are generally associated with severe storms and ET_o is generally not important during such conditions.

Temperature, Solar Radiation, and Humidity

Temperature, solar radiation, and humidity data usually follow a Fourier series distribution. Therefore, the model of these variables may be expressed as:

$$X_{ki} = \mu_{ki} (1 + \delta_{ki} C_{ki}) \qquad (1)$$

where k = 1, 2 and 3 (k=1 represents maximum temperature; k = 2 represents minimum temperature; and k =3 represents solar radiation). μ_{ki} is the estimated daily mean and C_{ki} is the estimated daily coefficient of variation of the ith day, i = 1, 2, … , 365 and for the kth variable.

SIMETAW simplifies the parameter estimation procedure of Richardson and Wright [4], requiring only monthly means as inputs. From a study of 34 locations within the United States, the coefficient of variability (CV) values appear to be inversely related to the means. The same approach is used to calculate the daily CV values. In addition, a series of functional relationships between the parameters of the mean curves and the parameters of the coefficient of variation curves, which made it possible to calculate C_{ki} coefficients from μ_{ki} curves without additional input data requirement, were developed.

Simulation Accuracy

Nine years of daily measured weather data (1990 – 1998) from the California Irrigation Management Information System (CIMIS) in Davis were used in the model to simulate 30 years of daily weather data. The weather data consist of R_s, T_{max}, T_{min}, wind speed, T_{dew}, and Rainfall. The weather data simulated from SIMETAW were compared with the data from CIMIS. Results in Figures 1, 2, and 3 showed that R_s, T_{max}, and Rainfall values predicted from SIMETAW were well correlated with those values obtained from CIMIS. Similar results were also observed for T_{min}, wind speed, and T_{dew} data.

Figure 1
Comparison of measured and simulated daily solar radiation data at Davis, California
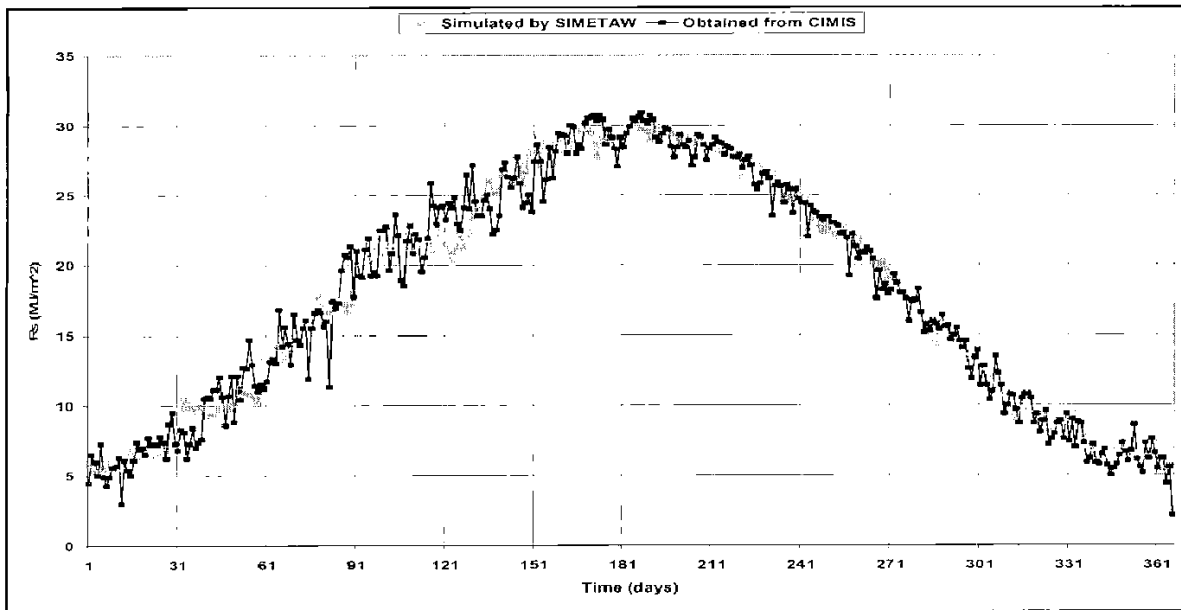

Figure 2
Comparison of measured and simulated daily maximum air temperature data at Davis, California
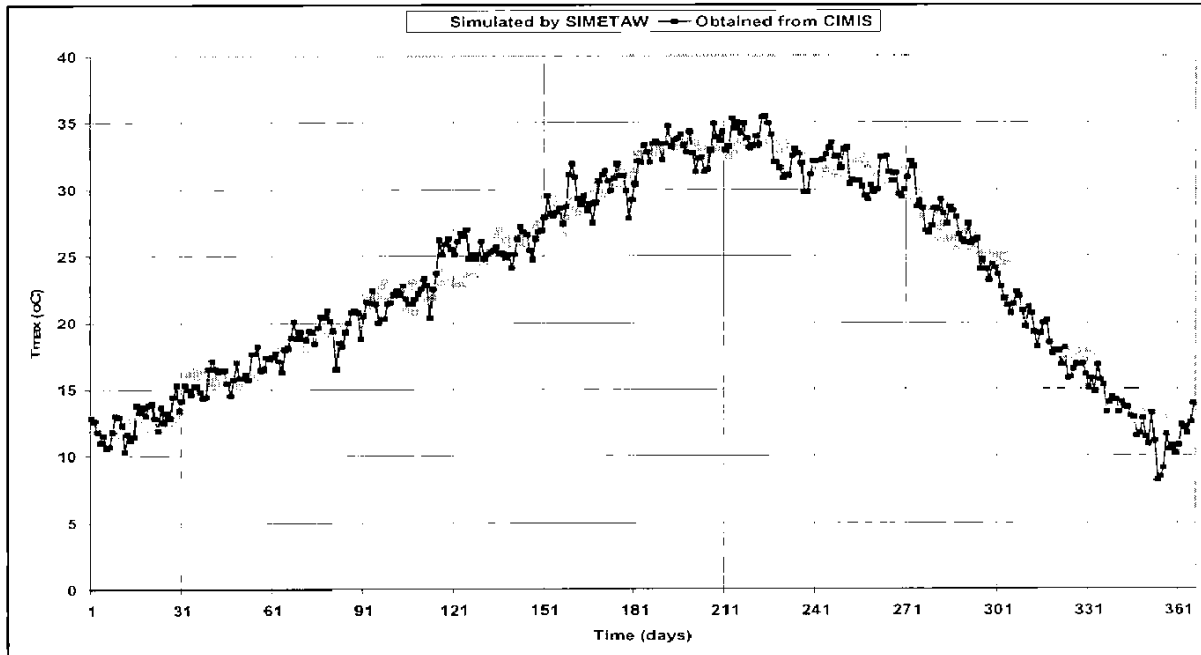
Figure 3
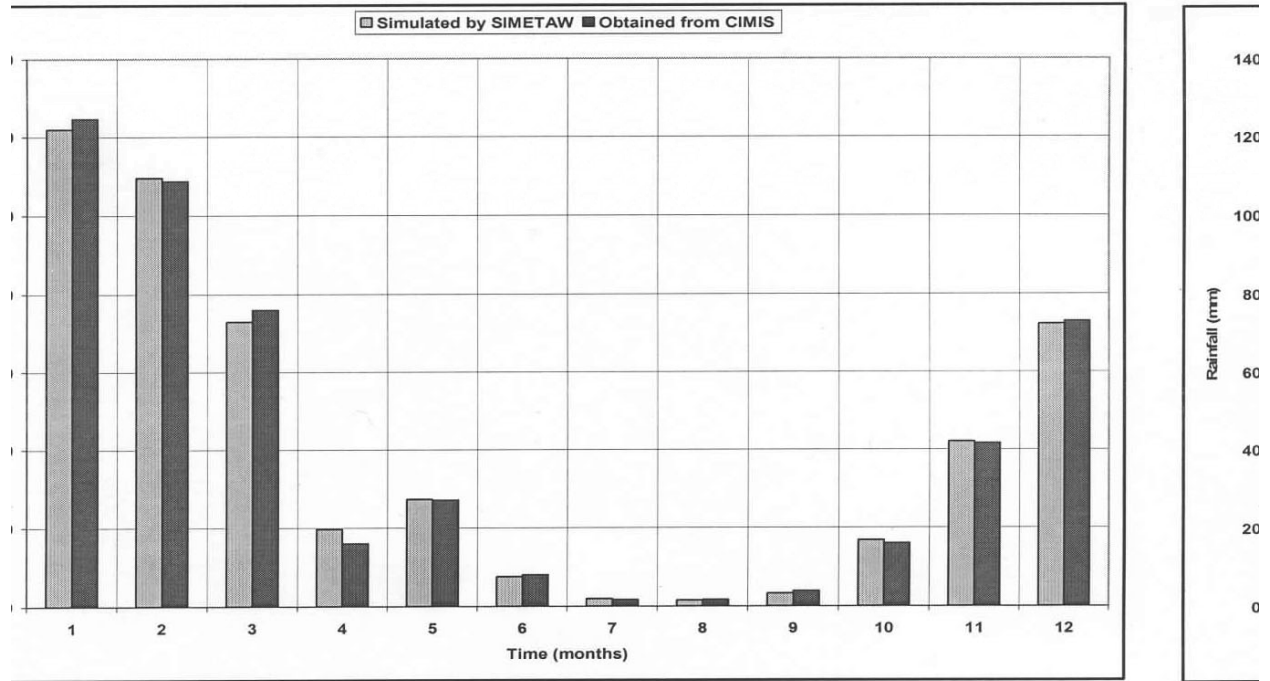**Comparison of measured and simulated monthly rainfall data at Davis, California**

Reference Evapotranspiration Calculation

Reference evapotranspiration (ET_o) is estimated from daily weather data using a modified version of the Penman-Monteith equation [5–7]. The equation is:

(2)

$$ET_o = \frac{0.408 \; \Delta \; (R_n \; - \; G) \; + \; \gamma \; \dfrac{900}{T \; + \; 273} \; u_2 \; (e_s \; - \; e_a)}{\Delta \; + \; \gamma \; (1 \; + \; 0.34 \; u_2)}$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve (kPa ^{o}C^{-1}), R_n and G are the net radiation and soil heat flux density in MJ m^{-2}d^{-1}, γ is the psychrometric constant (kPa ^{o}C^{-1}), T is the daily mean temperature (^{o}C), u_2 is the mean wind speed in m s^{-1}, e_s is the saturation vapor pressure (kPa) calculated from the mean air temperature (^{o}C) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature (^{o}C) for the day. The coefficient 0.408 converts the $R_n -$ G term from MJ m^{-2}d^{-1} to mm d^{-1} and the coefficient 900 combines together several constants and coverts units of the aerodynamic component to mm d^{-1}. The product 0.34 u_2, in the denominator, is an estimate of the ratio of the 0.12-m tall canopy surface resistance (r_c=70 s m^{-1}) to the aerodynamic resistance (r_a=205/u^2 s m^{-1}). It is assumed that the temperature, humidity and wind speed are measured between 1.5 m (5 ft) and 2.0 m (6.6 ft) above the grass-covered soil surface. For a complete explanation of the equation, see Allen and others [5]. If only temperature data are available, then the SIMETAW calculates daily ET_o using the Hargreaves-Samani equation. The equation may be written:

$$ET_o = 0.0023 \; (T_c + 17.8) \; R_a \; (T_d)^{1/2} \qquad (3)$$

Where T_c is the monthly mean temperature (degrees centigrade), R_a is the extraterrestrial solar radiation expressed in mm/month, and T_d is the difference between the mean minimum and mean maximum temperatures for the month (degrees centigrade).

If pan data are used in the program, then the program automatically estimates daily ET_o rates using a fetch value (i.e. upwind distance of grass around the pan). The approach in the SIMETAW provides a simple method to estimate ET_o from *Epan* data without the need for wind speed and relative humidity data. Verification of the Simulated Reference Evapotranspiration

As a final verification of the SIMETAW model, we compared our model predictions of ET_o with number of years of estimated daily ET_o data from CIMIS (California Irrigation Management Information System) at Davis, Oceanside, and Bishop. The performance of our model ET_o predictions was evaluated at sites influenced by coastal and windy desert climates. Figures 4, 5, and 6 compare daily mean ET_o estimates of SIMETAW and CIMIS averaged over the period of records. As seen in figures, a close agreement between CIMIS-based estimates of ET_o and those of the SIMETAW model exists. Bishop is influenced by a windy desert environment on the eastern side of the Sierra Nevada range. Oceanside is a coastal site in San Diego County. Davis is in the Central Valley, which is characterized by clear, hot, dry days with strong, cooling southwest winds during afternoons in the summer.

Figure 4
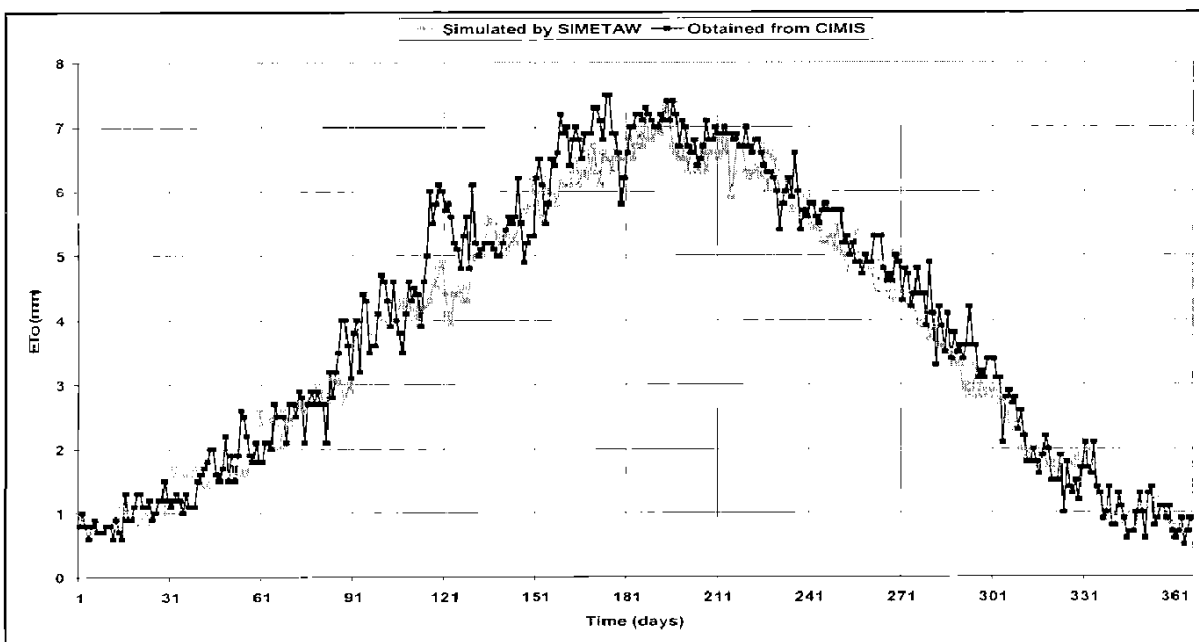**Comparison of daily ET_o estimates from SIMETAW and CIMIS at Davis, California**

Figure 5
Comparison of daily ET_o estimates from SIMETAW and CIMIS at Oceanside, California
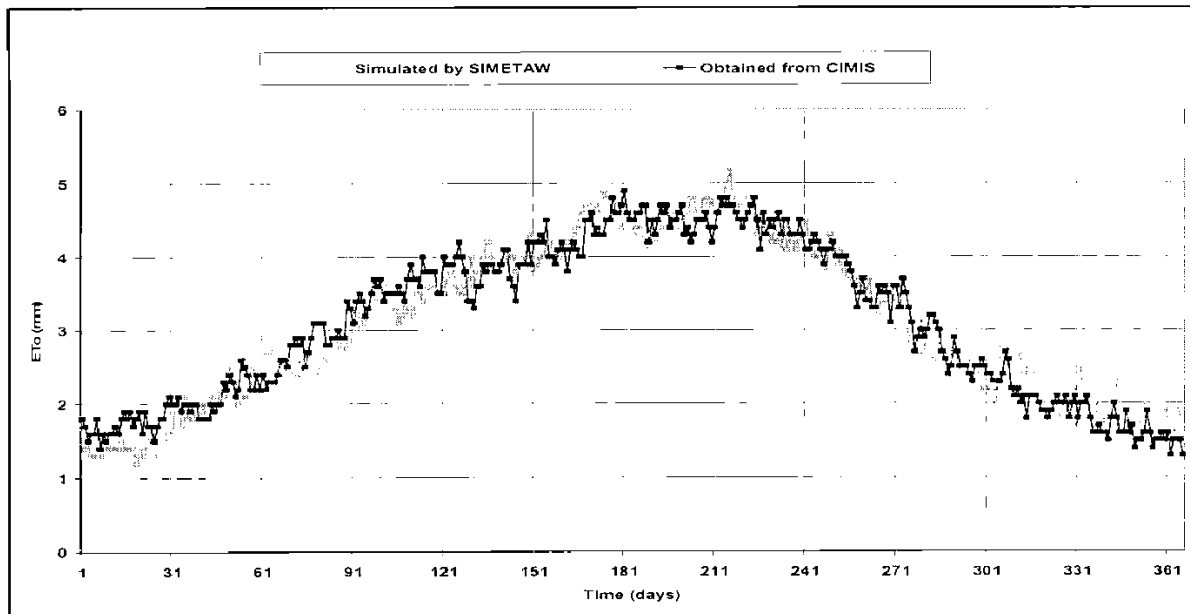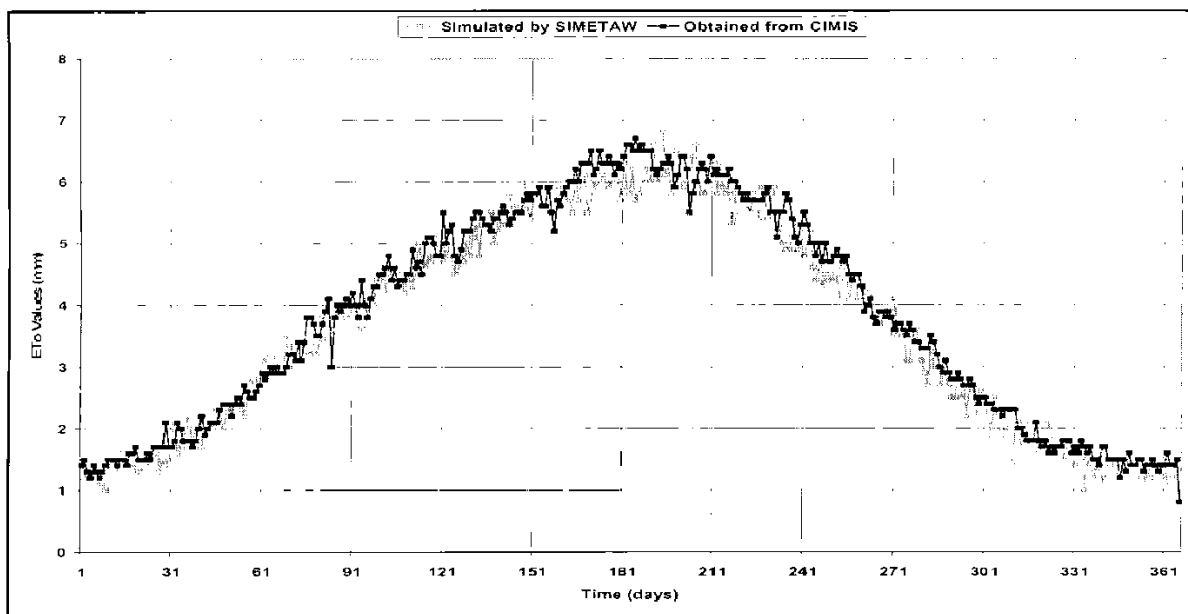

Figure 6
Comparison of daily ET_o estimates from SIMETAW and CIMIS at Bishop, California

Input Climate Data

Either daily or monthly climate data are used to determine ET_{aw} in SIMETAW. The daily data can come from CIMIS (California Irrigation Management Information System) or from a non-CIMIS data source as long as the data are in the correct format. After reading the data, ET_{aw} can be calculated directly from the raw daily data. In addition, the monthly means can be calculated from the daily files and then daily data

are generated using the simulation program. Since daily data were input directly, the calculation of monthly data for use in simulation of daily data is unnecessary. However, it was included to test if similar results are obtained using raw or simulated data.

The monthly data can be read from a file or calculated from daily CIMIS or non-CIMIS data files, or from some other source. The monthly data file must have the proper, comma-delimited format. SIMETAW will generate daily weather data for a specified period of record from the monthly data.

SIMETAW either generates a daily data file from monthly data or uses a raw data file consisting of daily solar radiation, maximum, minimum and dew point temperature, and wind speed for calculating daily ET_o. After calculating ET_o, if the data were generated, the program sorts the rainfall data within each month to force a negative correlation between rainfall amount and ET_o rate. Only the rainfall dates are sorted and there is no change in the dates for the weather and ET_o data. Further more, the program can simulate daily ET_o data directly from monthly means of ET_o and E_{pan} data.

Crop Coefficients

While reference crop evapotranspiration accounts for variations in weather and offers a measure of the 'evaporative demand' of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration and ET_o. The main factors affecting the difference are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration (ET) is the sum of evaporation (E) from soil and plant surfaces and transpiration (T), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. During early growth of crops, when considerable soil is exposed to solar radiation, ET_c is dominated by soil evaporation and the rate depends on whether or not the soil surface is wet. If a nearly bare-soil surface is wet, the ET_c rate is slightly higher than ET_o, when evaporative demand is low, but it will fall to about 80 percent of ET_o under high evaporation conditions. However, as a soil surface dries off, the evaporation rate decreases considerably. As a canopy develops, solar radiation (or light) interception by the foliage increases and transpiration rather than soil evaporation dominates ET_c. Assuming there is no transpiration-reducing water stress, light interception by the crop canopy is the main factor determining the ET_c rate. Therefore, crop coefficients for field and row crops generally increase until the canopy ground cover reaches about 75 percent. For tree and vine crops the peak K_c is reached when the canopy has reached about 70 percent ground cover. The difference between the crop types results because the light interception is somewhat higher for the taller crops.

Crop Coefficient Estimation

Crop coefficients are calculated using a modified Doorenbos and Pruitt [10] method. The season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods.

Field and Row Crops

Tabular default K_c values corresponding to important inflection points in Figure 7 are stored in the SIMETAW program. The value K_c1 corresponds to the date B K_c (K_cB). For field and row crops, K_c1 is used from date A to B. The value K_c2 is assigned as the K_c value on date C (K_cC) and D (K_cD). Initially,

the K_cC and K_cD values are set equal to K_c2, but for tree and vine crops, the values for K_cC and K_cD are adjustable for the percentage shading by the canopy to account for sparse or immature canopies. During the rapid growth period, when the field and row crop canopy increases from about 10 percent to 75 percent ground cover, the K_c value changes linearly from K_cB to K_cC. For deciduous tree and vine crops, the K_c increases from K_cB to K_cC as the canopy develops from leaf out on date B to about 70 percent shading on date C. During late season, the K_c changes linearly from K_cD on date D to K_cE at the end of the season. The values for K_cB and K_cC depend on the difference in (1) energy balance due to canopy density and reflective qualities, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop.

Figure 7
Hypothetical Crop Coefficient (K_c) Curve for Typical Field and Row Crops Showing Growth Stages and Percentages of the Season from Planting to Critical Growth Dates
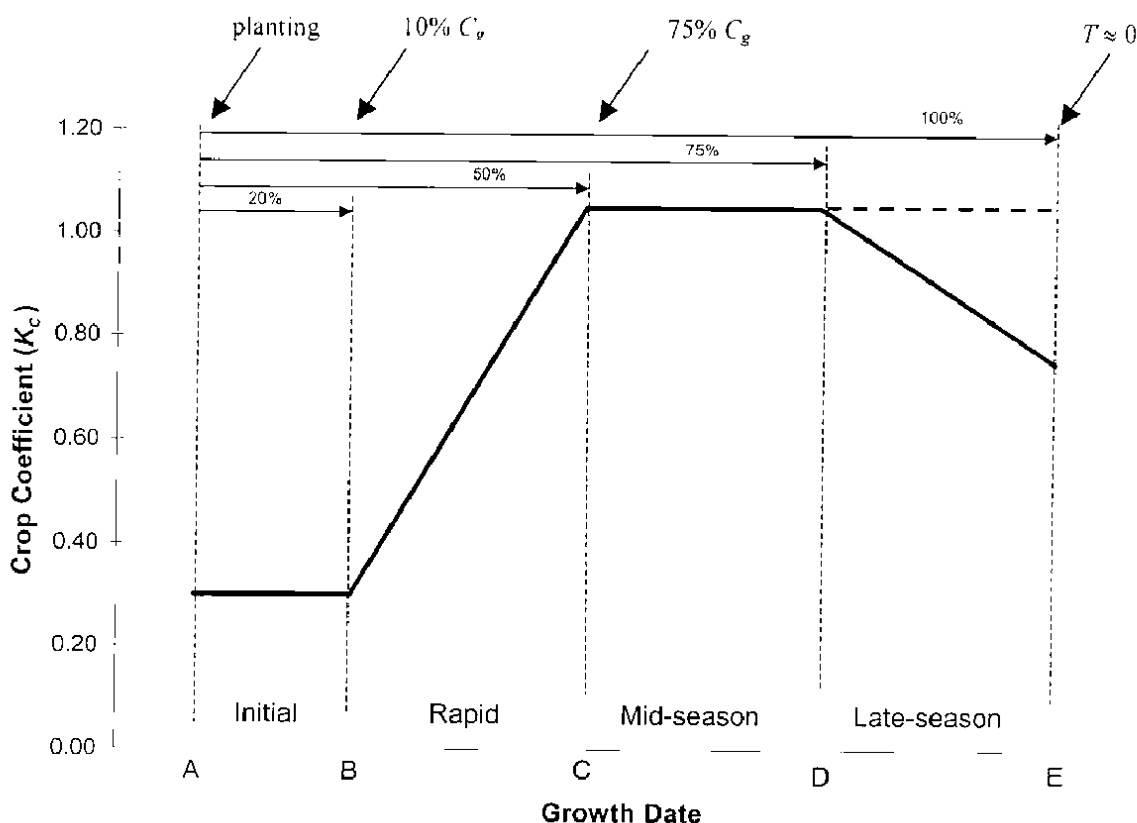
Deciduous Tree and Vine Crops

Deciduous tree and vine crops, without a cover crop, have similar K_c curves but without the initial growth period (Fig. 8). The season begins with rapid growth at leafout when the K_c increases from K_cB to K_cC. The midseason period begins at approximately 70 percent ground cover. Then, unless the crop is immature, the K_c is fixed at K_cC until the onset of senescence on date D ($K_c2=K_cC=K_cD$). During late season, when the crop plants are senescing, the K_c decreases from K_cD to K_cE. The end of the season occurs at about leaf drop or when the tree or vine transpiration is near zero.

Figure 8
Hypothetical Crop Coefficient (K_c) Curve for Typical Deciduous Orchard and Vine Crops Showing Growth Stages and Percentages of the Season from Leaf Out to Critical Growth Dates
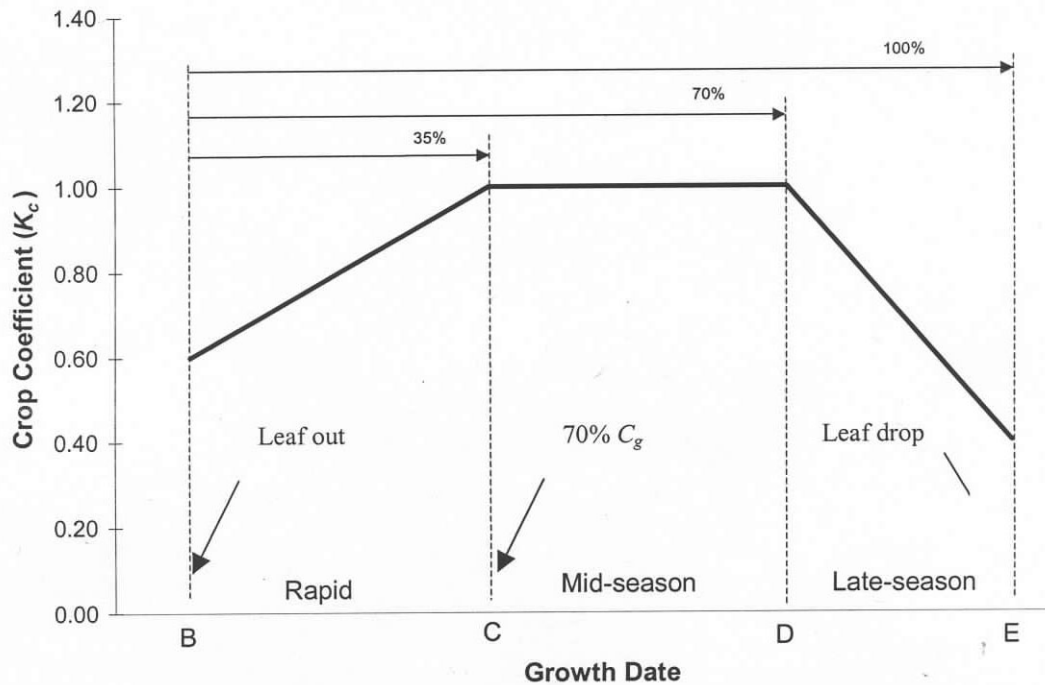
Correcting the Initial K_c for Wetting Frequency

During the off-season and during initial crop growth, E is the main component of ET. Therefore, a good estimate of the K_c for bare soil is useful to estimate off-season soil evaporation and ET_c early in the season. A two-stage method for estimating soil evaporation presented by Stroonsnjider [8] and refined by Snyder and others [9] is used to estimate bare-soil crop coefficients. As shown in Figure 9, this method gives K_c values as a function of mean ET_o and wetting frequency in days that are quite similar to the widely used bare soil coefficients that were published in Doorenbos and Pruitt [10]. In figure 9, solid lines represent the model used in the SIMETAW and dashed lines are from Doorenbos and Pruitt (1977). The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when $P_s > 2 \times ET_o$.

Figure 9
Crop Coefficient (K_c) Values for Nearly Bare-Soil Evaporation as
Function of Mean ET_o Rate and Wetting Frequency in Days
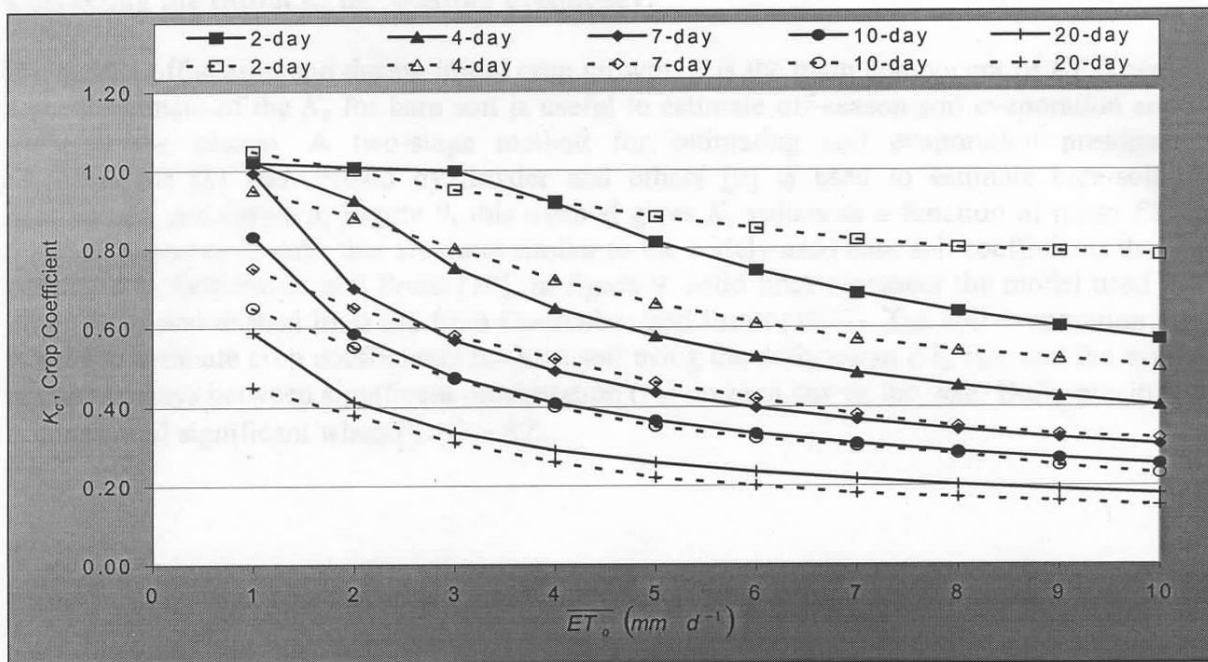
Correcting the K_c for Immature Trees and Vines

This program accounts for immaturity effects on crop coefficients for tree and vine crops. Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature K_c values (K_{cm}) as a function of percentage ground cover (C_g).

(4)

$$\text{If } \sin\left(\frac{C_g}{70}\frac{\pi}{2}\right) \geq 1.0 \text{ then } K_c = K_{cm} \text{ else } K_c = K_{cm}\left[\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)\right]$$

Correcting the K_c for Immature Subtropical Orchards

For an immature orchard, the mature K_c values (K_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

$$\text{If } \sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_{cm}\sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \qquad \text{V} \qquad \textbf{(5)}$$

Correcting for Cover Crops

With a cover crop, the K_c values for deciduous trees and vines are higher. When a cover crop is present, 0.35 is added to the clean-cultivated K_c. However, the K_c value is not allowed to exceed 1.15 or to fall

below 0.90. SIMETAW allows beginning and end dates to be entered for two periods when a cover crop is present in an orchard or vineyard.
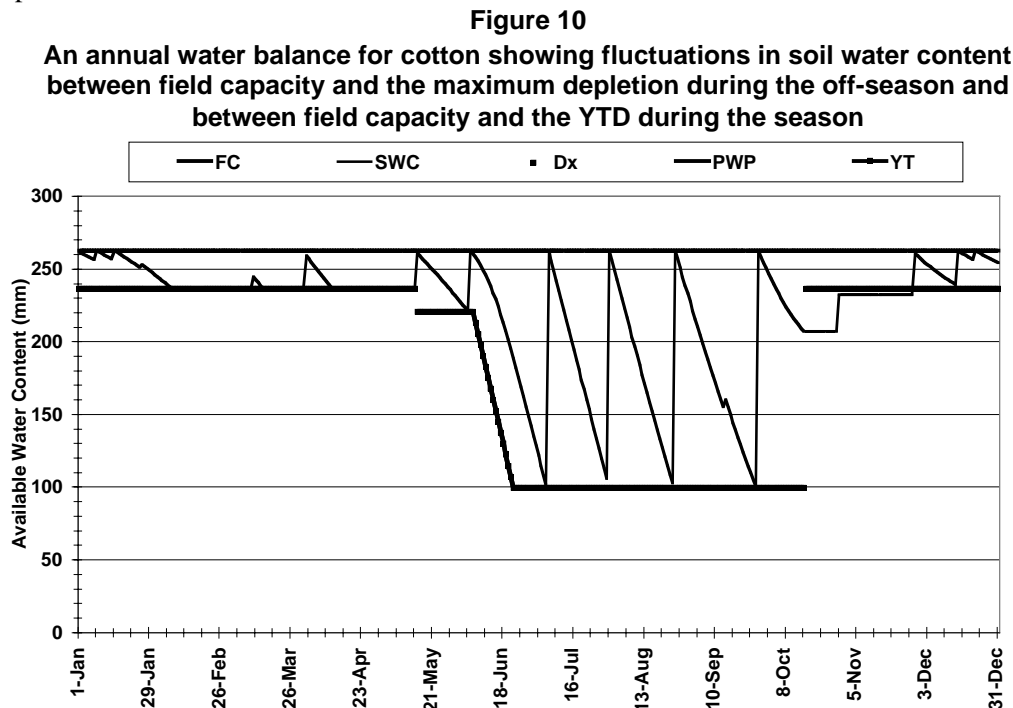
Field Crops with Fixed Crop Coefficients

Fixed annual K_c values are possible for some crops with little loss in accuracy. These crops include pasture, warm-season and cool-season turfgrass, and alfalfa averaged over a season. In the SIMETAW program, these field crops are identified as type-2 crops.

ET of Applied Water Calculations

The ET_o data come from the 'name.wrk' file, which is created from either input raw or simulated daily weather data. The K_c values are based on the ET_o data and crop, soil, and management specific parameters from a row in the 'DAUnnn.csv' file. During the off-season, crop coefficient values are estimated from bare soil evaporation as previously described. It is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Rainfall runoff as well as surface water running onto a cropped field is ignored. Because the water balance is calculated each day, this assumption is reasonable.

During the off-season, if the soil water depletion (SWD) is less than the YTD, ET_c is added to the previous day's SWD to estimate the depletion on the current day. However, the maximum depletion allowed is 50 percent of the PAW in the upper 30 cm of soil. If the SWD at the end of a growing season starts at some value greater than the maximum soil water depletion, then the SWD is allowed to decrease with rainfall additions but it is not allowed to increase with ET_c (Fig. 10). If half of the available water is gone from the upper 30 cm, it is assumed that the soil surface is too dry for evaporation. Once the off-season SWD is less than the maximum depletion, it is again not allowed to exceed the maximum off-season depletion.

Figure 10
An annual water balance for cotton showing fluctuations in soil water content between field capacity and the maximum depletion during the off-season and between field capacity and the YTD during the season

If a crop is pre-irrigated, then the SWD is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the SWD on the day preceding the season is determined by water balance during the off-season before planting or leafout. It is assumed that the SWD equals zero on December 31 proceeding the first year of data. After that the SWD is calculated using water balance for the entire period of record. During the growing season, the SWD depletion is updated by adding the ET_c (or by subtracting ET_c from the soil water content 'SWC') on each day (Fig. 3). If rainfall occurs, SWD is reduced by an amount equal to the rainfall. However, the SWD is not allowed to be less than zero. This automatically determines the effective rainfall as equal to the recorded rainfall if the amount is less than the SWD. If the recorded rainfall is more than the SWD, then the effective rainfall equals the SWD. Irrigation events are given on dates when the SWD would exceed the YTD. It is assumed that the SWD returns to zero on each irrigation date. The ETAW is calculated both on a seasonal and an annual basis as the cumulative ET_c minus the effective rainfall. The calculations are made for each year over the period of record as well as an overall average over years. The results are output to a summary table.

General Applications

Although the Simulation of Evapotranspiration of Applied Water (SIMETAW) program was written specifically to estimate ET_{aw} for estimating irrigation water requirements for use in water demand planning, the program is quite powerful and it has many additional applications. For hydrology, the SIMETAW application program can provide the evapotranspiration boundary conditions for ground and surface water models, which can lessen the potential for floods and can improve the management of water banking, aquifers, dams and reservoirs, and sea water intrusion in the Sacramento-San Joaquin Delta. In addition, the program can be used to help California growers to obtain improved crop coefficients for use in irrigation management. Use of SIMETAW to determine water demand by region can help with the management of water transfers throughout the State. Because the program generates many years of simulated weather data from monthly climate data, it can be used to study how changes in the monthly means might affect weather in the future. This can have implications as far as frost protection, which causes more economic losses in the United States than any other weather related phenomenon. Climatic changes in temperature, rainfall patterns, and humidity could all influence future daily weather conditions and could lessen or increase the probability of freezing temperatures. Changes in climate and the effect on daily weather can also influence air pollution within the State and SIMETAW can be used to simulate possible scenarios.

Air pollution is clearly a major problem in California and SIMETAW could help to identify an increased potential for major pollution events that could result from changes in rainfall patterns, temperature, etc. Another major problem in California is wildfire, which could worsen if the climate changes. SIMETAW can be used to study the impact of changes in monthly climate data on future weather conditions. This could impact biomass production in forests and rangeland, and changes in weather conditions could influence whether or not the natural ecosystems will experience more water stress and make them more prone to fire events. Of course, changes in the climate could impact on human health because of effects on air pollution as well as extremes of temperature. SIMETAW can provide scenarios of possible weather extremes resulting from changes in monthly climate data. SIMETAW can also be applied to refine the monthly mean ET_o rates (in/day) of California ETo Zone map. In addition, SIMETAW can be used as a tool to fill in missing data points from long-term data sets, which could be helpful for developing rainfall-runoff models, etc. Currently, there is considerable research on the use of regulated deficit irrigation (RDI) to more efficiently use water in crop production, which could potentially decrease water demand.

The SIMETAW program has a stress factor built in to account for reductions in ET_{aw} due to the use of RDI.

More information on SIMETAW is available at DWR's Web site:

www.waterplan.water.ca.gov/landwateruse/wateruse/Ag/wuagricultural.htm

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